U.S. Coast Guard Research and Development Center

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Report No. CG-D-12-99

MARINE MOLTEN CARBONATE FUEL CELL DEMONSTRATION MODULE

USCGC VINDICATOR SHIP INTERFACE STUDIES

FINAL REPORT
MAY 1999

Prepared for:
U.S. Department of Transportation
United States Coast Guard
Operations (G-O)
Washington, DC 20593-0001

N O T I C E

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Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-12-99	ADA368291	
4. Title and Subtitle Marine Molten Carbonate Fuel Cell Demonstration Module USCGC VINDICATOR Ship Interface Studies		5. Report Date May 1999 6. Performing Organization Code Project No. 3310.2 / UDI 85
7. Author(s) Zvi Karni and Peter Fontneau		8. Performing Organization Report No. R&DC 09/99
1. Performing Organization Name and Address John J. McMullen Associates, Inc. 4300 King Street, Suite 400 Alexandria, VA 22302	U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, CT 06340-6096	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTCG39-95-D-E99010
12. Sponsoring Organization Name and Address U.S. Department of Transportation United States Coast Guard Operations (G-O) Washington, DC 20593-0001		13. Type of Report & Period Covered Final 14. Sponsoring Agency Code Commandant (G-OCU) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

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16. Abstract (MAXIMUM 200 WORDS)

In this study, the U.S. Coast Guard (USCG) investigated the impact upon CGC VINDICATOR ship systems resulting from potential conversion to fuel cell propulsion and auxiliary power. VINDICATOR is a T-AGOS class monohull, 224-feet in length, powered by four Caterpillar diesel-electric generators with DC propulsion motors. USCG selected this vessel as a candidate for development and potential demonstration of fuel cell power on board ships. Space and weight limitations and marine operational requirements uncovered during this study are believed to be applicable to other ship installations. Detailed changes to structural, electrical, fuel delivery, exhaust management and related systems necessitated by removal of the four main diesel generators and replacement by four molten carbonate fuel cell modules were developed. Also developed was the outline design of each 625 kW molten carbonate fuel cell Demonstration Module, including fuel processing, fuel cell stacks, and inverter. A dynamic computer simulation model was created which linked the fuel cell performance to ship parameters including displacement, speed, and loading cycles. This information was used to analyze the ship integration impacts based on the fuel cell design. Included with this final summary report are outline figures of detailed removal and installation drawings detailing existing and proposed arrangements.

Several conclusions are made. The proposed fuel cell modules are compatible with existing ship interfaces, with relatively minor modifications. The fuel cell modules are substantially larger than the diesel generators they replace, necessitating removal of the non-structural side shell within the main diesel generator room. Existing air handling, exhaust, and fuel delivery systems can be reused, ship performance (stability and seakeeping) is unchanged, and minor maneuvering performance changes may result. Increased range is expected due to the predicted higher efficiency of the fuel cells. Overall, the installation and operation of fuel cells on this ship appears to be technically feasible.

17. Key Words	18. Distribution Statement
molten carbonate, fuel cell, diesel generators, electric propulsion system, design simulation, maneuvering performance, stability, seakeeping, required performance, transient equations	This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

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EXECUTIVE SUMMARY

In this study, the U.S. Coast Guard investigated the impact upon CGC VINDICATOR ship systems resulting from potential conversion to fuel cell propulsion and auxiliary power. VINDICATOR is a T-AGOS class monohull, 224 feet in length, and powered by four 600 kW Caterpillar diesel-electric generators with DC propulsion motors. The USCG selected this vessel as a candidate for development and potential demonstration of fuel cell power on board ships. However, space and weight limitations and marine operational requirements uncovered during this study are believed to be applicable to many other future ship installations. Detailed changes to structural, electrical, fuel delivery, exhaust management and related systems necessitated by removal of the four main diesel generators and replacement by four molten carbonate fuel cell modules were developed.

A conceptual arrangement of the machinery space and interfaces with auxiliary systems was developed. The volume of the fuel cell system was more than two-and-a-half times that of the generators they replaced. The larger dimensions, length, height and width of MC fuel cells compared to diesel generators, require modifications in the machinery room. In particular, removal of the void bulkheads on both sides of the machinery room is required in order to provide access to the four fuel cell modules. The machinery service systems, seawater, lubrication oils, fresh water, fuel and compressed air are all affected, although to a relatively minor degree.

Since the fuel cells' weight and center of gravity were similar to those of the generators, the ship's performance in terms of stability and sea keeping are expected to remain unchanged. Limited maneuvering simulations, ship forward acceleration and reversing, were performed. These simulations showed that the application of power produced by fuel cells is expected to cause insignificant changes in the maneuvering performance of the ship.

The power generation and distribution systems for the ship were originally designed to comply with the Type 1 power requirements of DOD-STD-1399, Section 300. This DOD standard requires diesel generator sets to comply with the transient load requirements of MIL-G-21296 and MIL-G-21410, and to ensure that the system power quality is maintained during large load transients. Molten Carbonate Fuel Cells do not fully comply with these criteria. With the current load limiting features inherent in the propulsion system drive controls, the transient response from the currently designed fuel cells is expected to perform well for ship maneuvering power requirement. However, similar to most advanced, highly turbocharged diesel generators, the short term transient response does not fully support the requirements of DOD-STD-1399 or the IEEE-STD-45 equivalent. Steps to enhance instantaneous transient response can be incorporated into either the consumer side, or the fuel cell system itself. These can include incorporation of energy accumulators or capacitors in the system. A similar problem occurs with automobiles where improved acceleration is achieved by adding turbochargers to small engines (in terms of cylinders and cylinder size) or by using multiple power sources such as adding electric battery driven motors to the power system.

This final report also provides the technical summary of the Dynamic Simulation Model (DSM) development for the Molten Carbonate, Coast Guard Fuel Cell (MCFC) power plant. It lays the foundation for computer programs and software coding of the DSM and incorporates the vessel's electric propulsion system as a controlled large load typical to ships with an integrated electric propulsion system. A narrative description of the MCFC power plant operation and control strategy is also provided. The governing transient equations related to the fuel cell and the fuel processing are described in detail in the Dynamic Simulation Model (DSM).

The conversion of the power generation system of the USCGC VINDICATOR appears technically and physically feasible. There is sufficient volume and surface area to accommodate equal power Molten Carbonate fuel cells. The interface to the ship's systems is technically feasible.

The impact upon performance is, however, noticeable. Higher thermal efficiency, significantly better part load performance, increasing endurance (range), and reduced vibrations, noise and emissions outweigh the non full-compliance with short-term transients. This is especially true in light of the trend to diesel generator (DG) or turbo-generator (TG) powered ships. This trend has been seen in current designs of cruise ships and U.S. Navy ships for vessels for coastal warfare, in a partial load loitering condition such as research vessels, or where thermal emissions are critical.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

TABLE **PAGE**

1.0 INTRODUCTION

In late 1997, John J. McMullen, Associates, Inc. (JJMA) was tasked to develop a conceptual arrangement for replacing the existing Caterpillar diesel generators with new technology Molten Carbonate Fuel Cell (MCFC) for powering the USCGC VINDICATOR (see Figure 1). The VINDICATOR is a TAGOS-1 Class ship with an integrated DG electric propulsion system. The current generator/propulsion system consists of four Caterpillar diesel generators, 60 Hz, 600 kW each, electrical distribution boards, and two 800 horsepower direct current (DC) propulsion motors driving two fixed pitch (FP) propellers. The overall task is to design the replacement of four Caterpillar diesel generators with equivalent power capacity MCFC modules of 625 kW each. The arrangement design of the engine room using the MCFCs took into account the required ship interfaces, operational scenarios, environmental requirements and ship impacts. A series of deliverables have been produced to support this effort including the following:

- Shipcheck report
- Fuel Cell Demonstration Module design report
- Preliminary conceptual engine room arrangement
- Arrangement of the machinery space and auxiliary systems interfaces to support fuel cell installation.
- Literature search of available simulation tools to be used with the Dynamic Simulation Model (DSM)
- Outline of proposed DSM
- Final DSM report

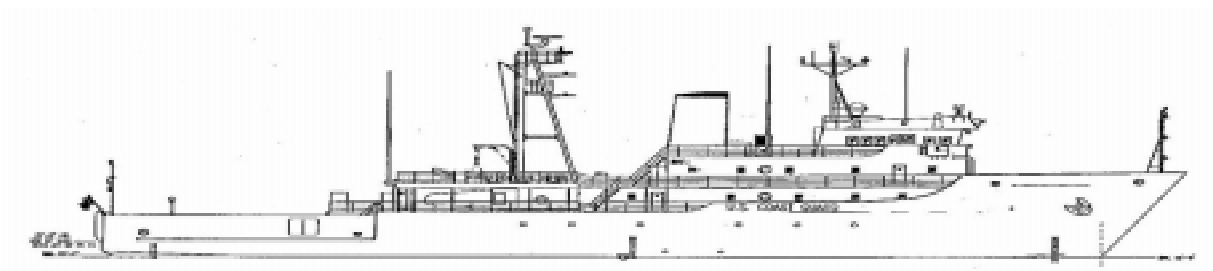


FIGURE 1. USCG VINDICATOR

The initial conceptual arrangement of the machinery space and the interface with the ship's auxiliary systems required to support the fuel cell installation were defined following a December 1997 shipcheck of the USCG VINDICATOR. The first machinery space arrangement utilized initial fuel cell design constraints of arrangement and packaging of the fuel cells as a one-to-one replacement of a diesel generator by a fuel cell module. Factors considered were:

- Commonality with U.S. Navy power module requirements,
- Dimension constraints to an ISO short container (20 ft x 10 ft x 8 ft), and
- Realistic ship interfaces for fluids, exhaust, and power conditioning.

As the FC module design evolved, various arrangement options were produced incorporating dimensional changes in the design of the fuel cell. A set of removal and installation drawings was produced and presented at the first design review on February 1998. The Fuel Cell Demonstration Module Preliminary Design Report was produced on May 22, 1998. It introduced the developments since February 1998 with an emphasis on the demonstration module design and its effect on the machinery arrangement.

The second part of the task was to develop a dynamic simulation model. The Dynamic Simulation Model (DSM) has been used to simulate the maneuvering performance of the USCGC VINDICATOR using a MCFC and comparing the results to the performance characteristics of the ship using the current Caterpillar diesel generators. The simulation model allows the gathering of data on differing operational parameters such as varying patrol speed and direction, MCFC performance, and system transient response. While limited maneuvering simulations have been performed, DSM simulations show that the application of power as produced by the MCFC is expected to cause insignificant changes to the maneuvering performance of the ship. The MCFC response to rapid power requirement changes was not simulated. It is clear that just as with the responses of turbo charged diesel generators, the MCFC will have compliance difficulties with instant major power demand changes. It is believed that the use of design features such as accumulators or capacitors will improve the short term transient response of the MCFC. Additionally, simulations demonstrated that the fuel “pre-processing” step was the primary contributor to the delay of the MCFC system’s response to power requests.

2.0 SHIP AND MACHINERY ROOM ARRANGEMENTS

The conceptual arrangement of the machinery space and the interface with the auxiliary systems required to support the fuel cell installation were defined following the December 1997 shipcheck. A set of removal and installation drawings was produced and presented at the first design review on February 1998.

The February 1998 arrangement was based on the main premise that four 625 kW fuel cells can be packaged to occupy, essentially, the same space that the four Caterpillar diesel generators currently occupy. It has been determined since then that the dimensions of the fuel cell modules are larger than anticipated and that packaging of four fuel cell units into the existing machinery space is a challenge. A study was commissioned to recommend whether three (3) modules in lieu of four (4) modules would be acceptable. The study findings and the recommendation to proceed with a four module arrangement are presented in this report.

Several arrangement options designed to accommodate a four-module assembly were produced. Their designs attempt to minimize changes to the ship's hull structure and stiffeners, and to enable utilization of most of the existing fluid systems. The last arrangement, Option 5, takes into account the most recent change in the module's width dimension from 7 feet to 7 feet-4 inches. This forces utilization of the voids on both sides of the machinery room.

At this time, it is still felt that the development of the fuel cell has not reached the stage where the conceptual design, arrangements, structure, piping and control system can be completed for a specific ship. The following sections present the impacts resulting from installation of the fuel cells on the ship. The technical evolution is presented in order to preserve the process that will lead to the final arrangement that will be able to accommodate the fuel cells that are under development and to provide the common background to the engineers that are participating in the process.

2.1 Access

The access for installation and later for maintenance is an upper deck softpatch over the Motor Generator Room (MGR) entrance trunk, starboard side, FR 45+ to 51+. The approximate size of the softpatch is 5 feet-9 inches x 11 feet-6 inches. All gratings and ladders in the clear area of the trunk are removable. The Halon line across the forward end of the access space just below main deck is removable. Several electrical features (lights, exit light, emergency lighting) may interfere with access at the forward end of the opening at the forecastle deck. Within the machinery room, the large components will be installed using overhead rails and temporary chains and lifting equipment. The installation of the four fuel cells will probably commence via side shell openings at a dry dock. The largest components that are to be maintained periodically are the 3 feet x 5 feet x 8 feet high, 12,000 lbs. fuel stacks.

2.2 Arrangement Envelope

It is desired to constrain the box dimensions of each fuel cell module to approximately 16 feet-9 inches x 7 feet x 9 feet (L x W x H). The removal of the DGs, their foundations and their fluid support systems will provide a 15 foot long clear space. Removal of grating, both forward and aft of the DGs, up to the sea water headers will provide another 1 feet 9 inches to the clear length. This will enable passages for maintenance, and require no modification to the ships' stanchions in the machinery room. Option 1, shown in the following arrangement drawing, Figure 2, provides the minimum packaging dimensions based on the seven-foot wide modules.

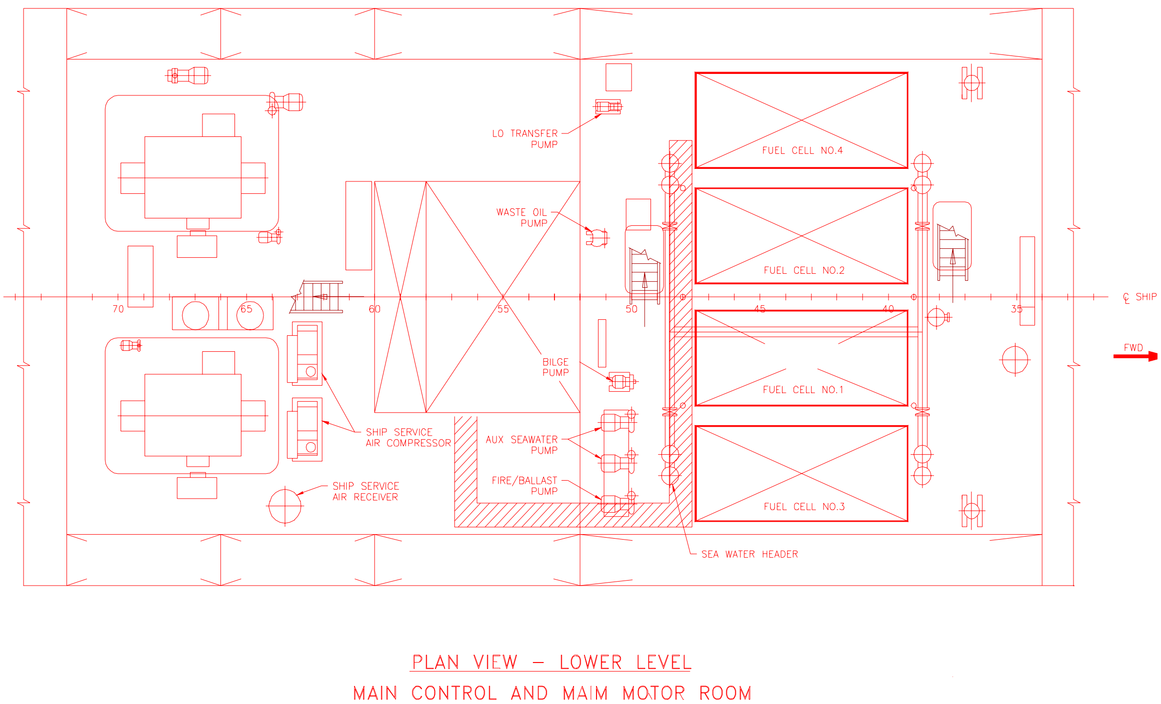


FIGURE 2. ARRANGEMENT OPTION 1

2.3 Arrangement Options Evolution

Unfortunately, the expected dimensions of the individual modules will, probably, be larger. The February 98 length dimension was shown as 26 feet, of which 3 feet could be separately installed. The 7-foot width allowed for 12 inch spacing between the modules and the longitudinal bulkheads of the voids on both sides of the machinery room. The center path width was 24 inches wide while 18 inches existed on the other passages. Typical removal plan views for the upper level and lower level for all arrangement options are shown in Figures 3 through 5.

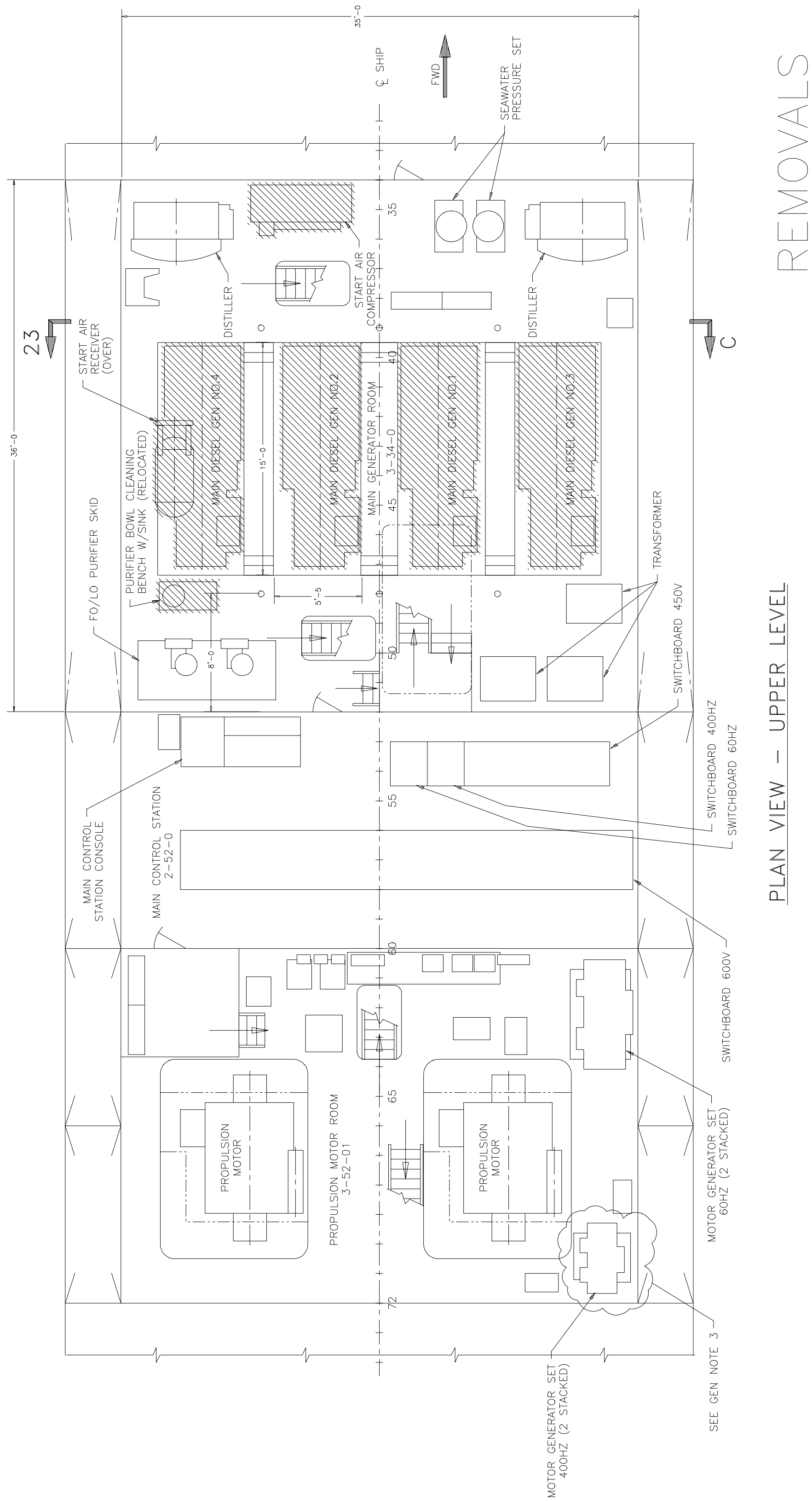


FIGURE 3. REMOVALS (PLAN VIEW TYPICAL) – UPPER LEVEL

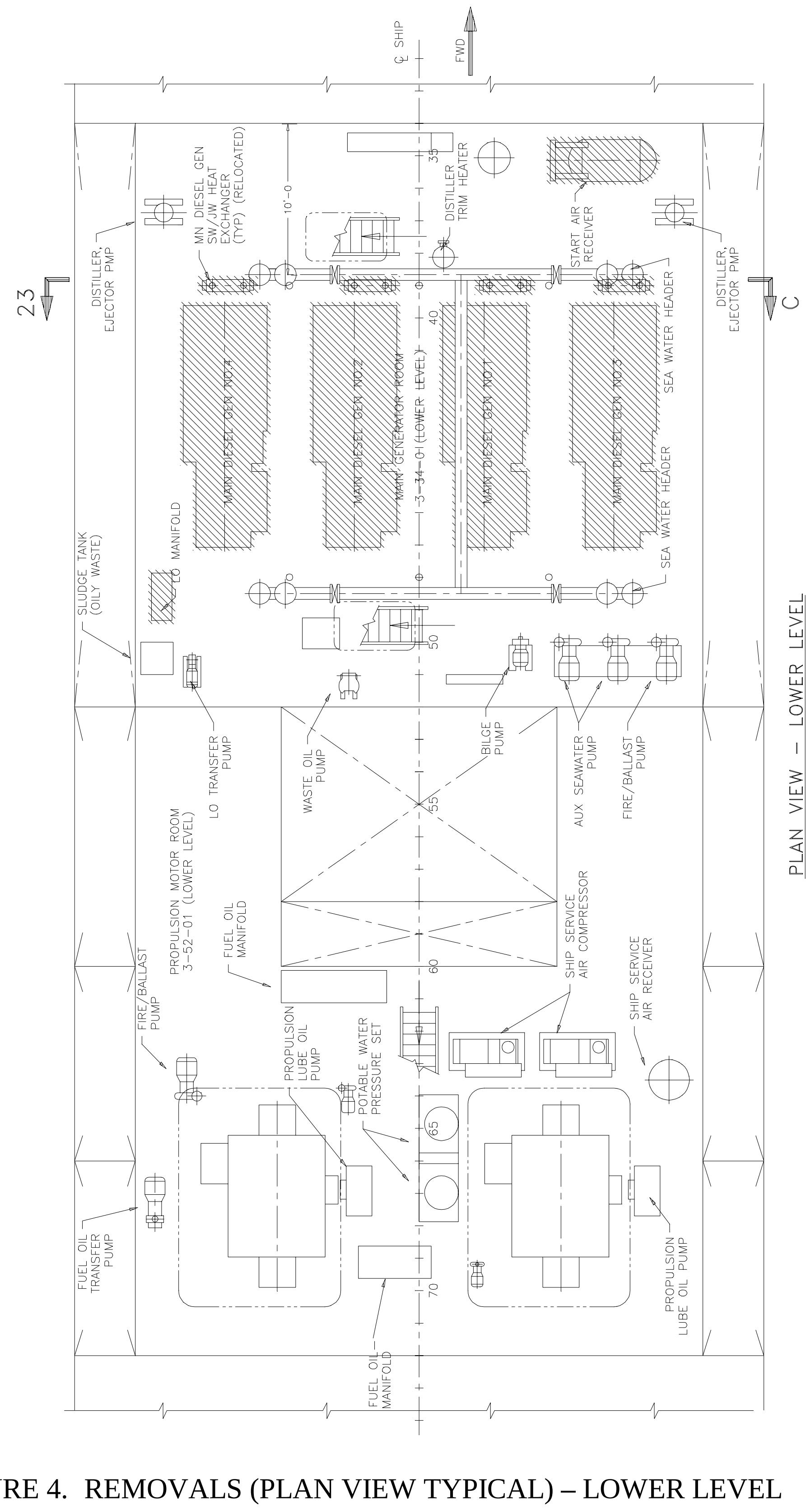


FIGURE 4. REMOVALS (PLAN VIEW TYPICAL) – LOWER LEVEL

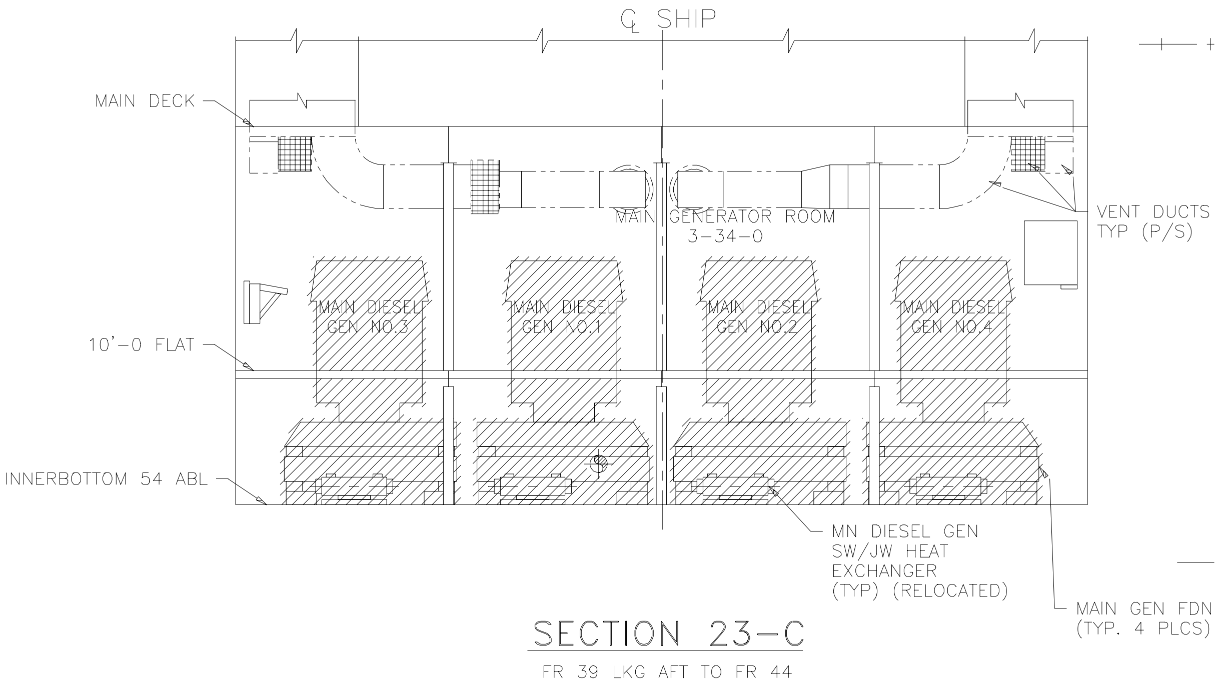


FIGURE 5. DIESEL GENERATOR REMOVALS (SECTIONAL TYPICAL)

2.3.1 Options 2, 3, and 4

Options 2 through 4 were adjustments and refinements to Option 1. Option 2 increased the fuel cell module length by almost 4 feet from that used in Option 1 to a length of 20 feet-6 inches. This length included the 3-foot control module and required rotation of the Nirex watermakers, relocation of the forward transformer, the Motor Control Center (MCC), and the existing seawater piping interfaces. Option 3 was a result of attempting to create room for maintenance on the aft end of the fuel cell modules. The fuel cells were moved forward resulting in replacing the Nirex water makers with Reverse Osmosis (RO) units, which were placed one on-top of the other. This resulted in requiring HVAC ducting modifications and seawater piping relocations, but allowed the forward transformer to return to its position in Option 1. The height of the fuel cell module was now 11 feet-6 inches without the MCC. Option 4 moved the RO units to the forward port side of the Machinery Room and a penetration was made into the starboard void to enable the relocation of the transformer. Additionally the lower forward module skid was stepped up so as to have minimum modifications to the forward seawater main. By this time the fuel cell modules were 7 feet-4 inches wide after allowing for noise insulation of the enclosure. This, for all practical purposes, eliminated any passages between the fuel cells. The investigation into utilizing the voids on both sides of the machinery room resulted in Option 5.

2.3.2 Option 5

Option 5 expands the passageways to 36 inches and allows relocation of the auxiliary electrical board to the machinery space forward bulkhead. See Figures 6 through 8 for

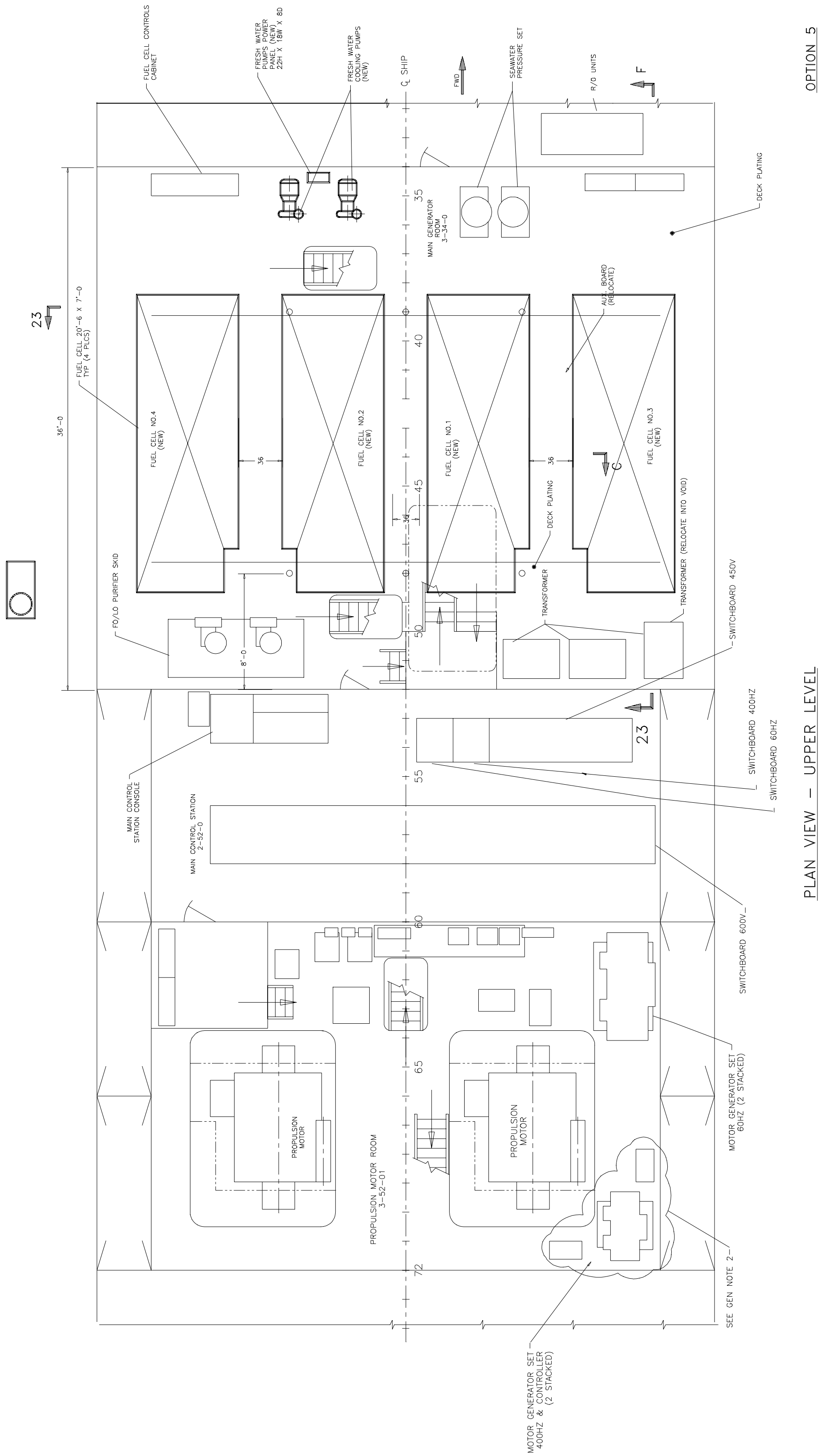


FIGURE 6. OPTION 5 ARRANGEMENT – PLAN VIEW UPPER LEVEL

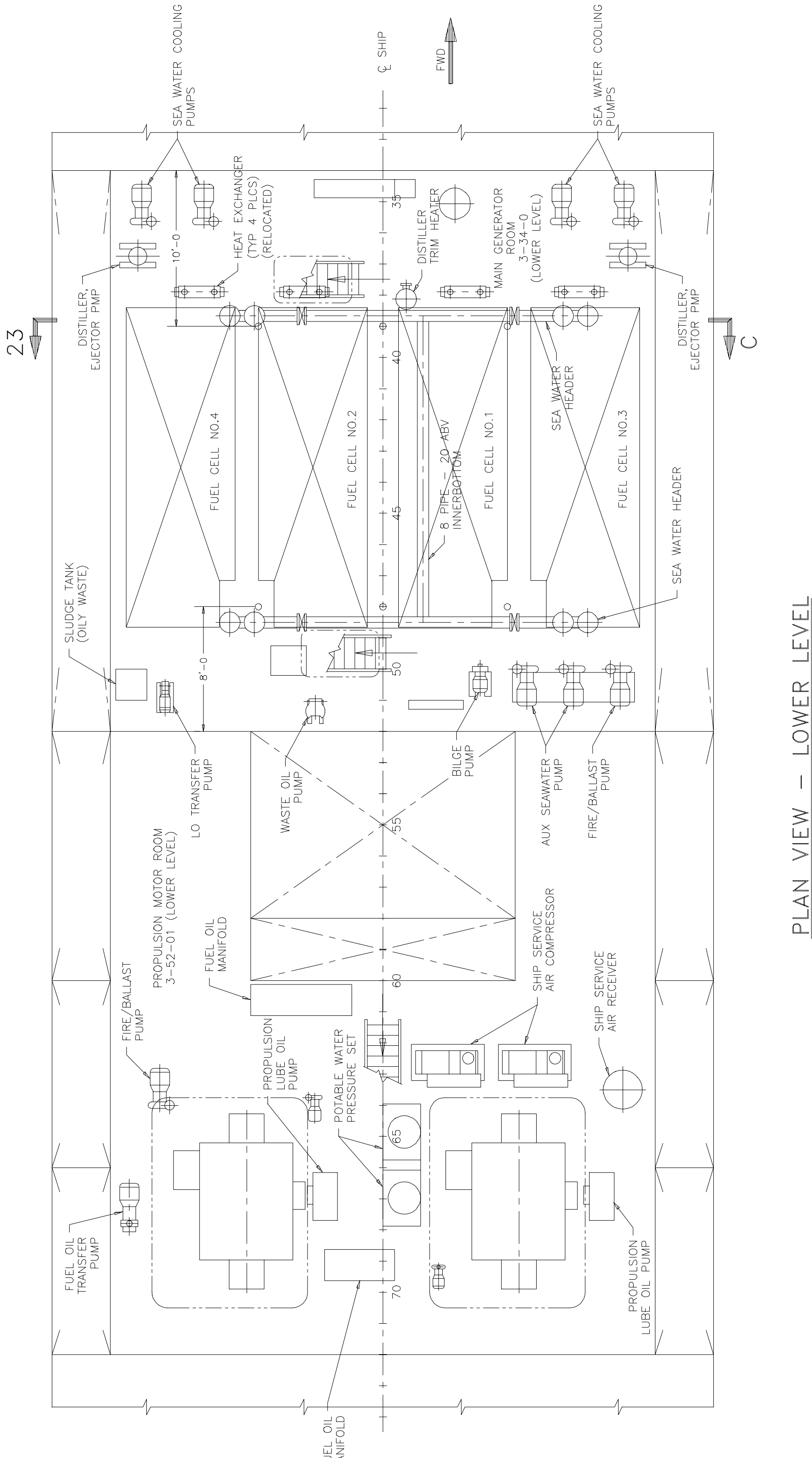
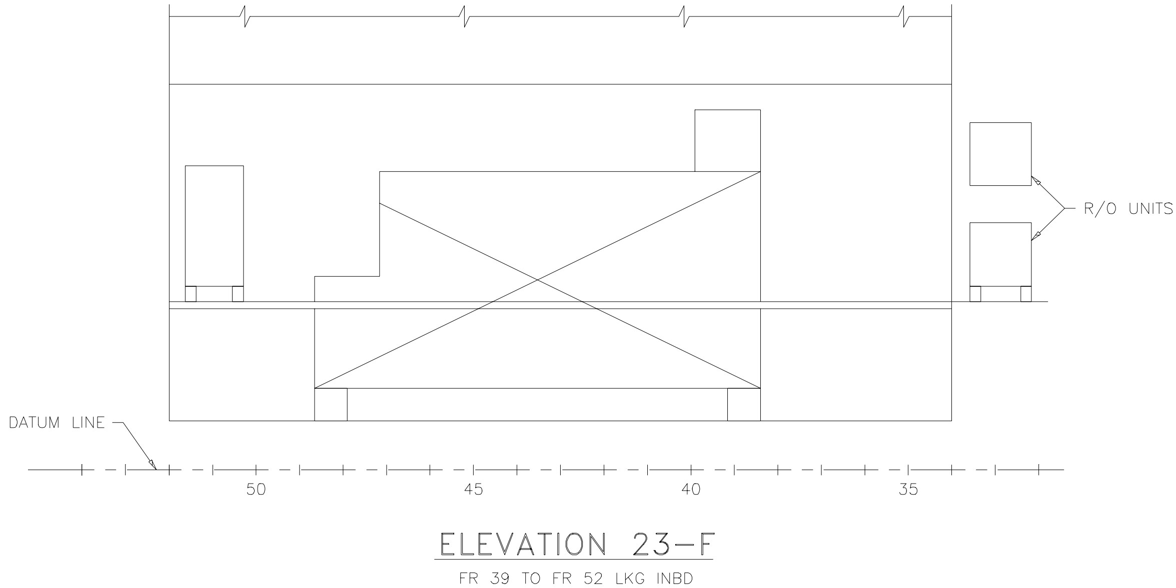


FIGURE 7. OPTION 5 ARRANGEMENT – PLAN VIEW LOWER LEVEL



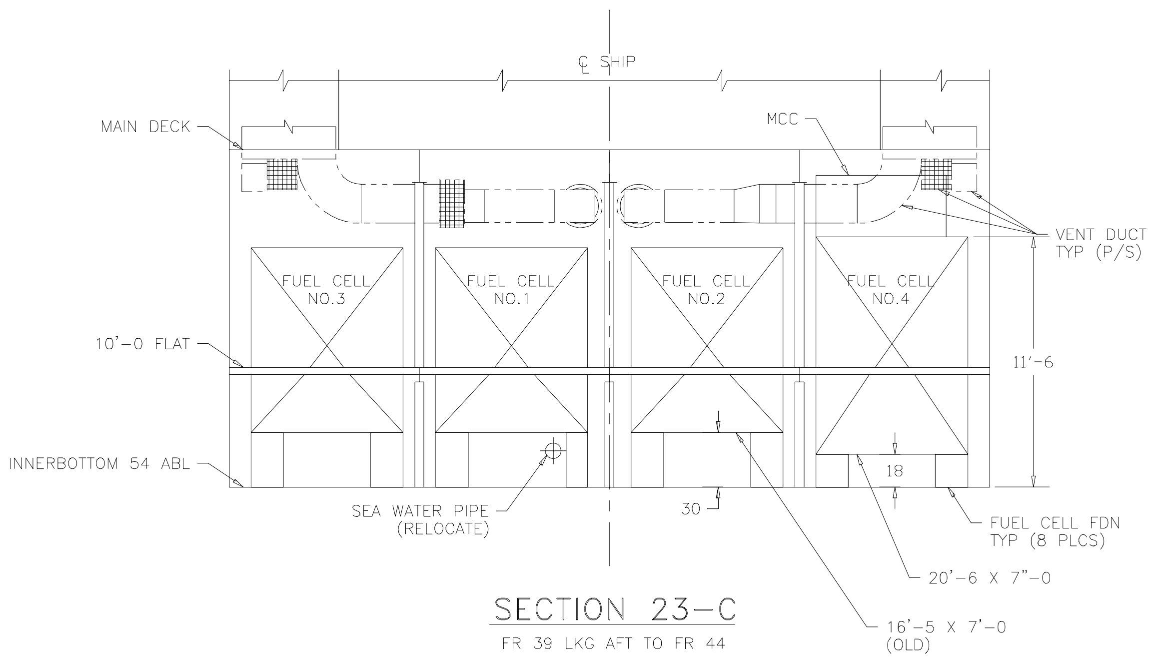


FIGURE 8. OPTION 5 ARRANGEMENT – ELEVATION AND SECTIONAL

the upper and lower level plan views of Option 5. The modules can be slid forward to allow for sufficient space for fuel stack maintenance. The control cabinet for the four units is installed on the port side of the machinery forward bulkhead. In addition the RO units were relocated outside the Machinery Room to the laundry space forward of the machinery space.

Since the fuel cell weight and center of gravity were nearly identical to those of the diesel generators, no changes to stability are expected. A preliminary structural check also revealed that the proposed configuration is feasible. Once the detailed development of the fuel cell design is completed, it will be integrated into the final arrangement drawings. A discussion regarding the structural modifications to the voids follows.

2.3.3 Utilization Of Voids - Structural Considerations

The void spaces into which the fuel cells are to be placed currently consist of the longitudinal bulkhead and side shell structure with a side stringer at approximately mid-height. There are transverse diaphragms between the side shell and bulkhead along with transverse stiffeners on the side shell and bulkhead.

The transverse stiffeners on the side shell are 6 x 3 ½ x 5/16 L with a section modulus of approximately 10 in^3. Assuming the side stringer will no longer be capable of supporting these stiffeners means their design span will approximately double and the required section modulus increase by a factor of 4, i.e. SMreqd = 40 in^3. This can be efficiently supplied by a stiffener 12 inches to 15 inches deep.

Also, as much of the bulkhead should be left intact as possible to retain the longitudinal plane of support and minimize stress concentrations due to breaks in continuity.

There may be many options open when the final design is developed; however, preliminary estimates indicate there will be no problem providing the required structure.

2.4 Plant Configuration - Three Vs. Four modules

Currently, four 600 kW Caterpillar diesel generator sets provide power for the propulsion, auxiliary, mission support and hotel loads which are fed from the integrated electric plant. Main propulsion and associated auxiliaries have a functional load of 1351 kW, largely determined by the size of the installed electric propulsion motors. The total required power, without growth margin, can be provided by any 3 of the four main diesel generators installed. At this power level, the ship achieves a top speed of 11.5 knots, approximately. The primary complaint from the ship's operators has been the low maximum speed of approximately 12 knots.

The design task calls for the removal of the four 600 kW diesel generator sets and the installation of an equivalent Molten Carbonate Fuel Cell power production system. The installation of four fuel cell modules, each rated at 625 kW, will provide a total of 2500 kW. This exceeds the current capacity of 2400 kW. Because of space constraints within the machinery room, the option of using three modules in lieu of four was considered. Installation of three fuel cell modules would provide a total system power level of 1875 kW.

2.4.1 Impact Analysis - Arrangements

Arrangement of the fuel-cell units within the existing generator room is not limited to longitudinal orientation as is required for conventional rotating machinery. This fact, combined with the use of three fuel-cells vice four, will allow for a cleaner machinery space in which to operate and perform maintenance.

The task calls for packaging each fuel cell module within a 20 feet length. The allocated space is approximately 3 feet shorter, but sub-modules can be located outside of the 17 feet allocation and the available machinery room height can be utilized.

2.4.2 Electric Power Load Analysis

As shown in the newly revised electric plant load analysis (see Table 1) only three units are required at any one time for the ship's current operational scenario. The use of the fourth unit serves to provide load growth capability, reduced annual operating hours per unit, and redundancy.

TABLE 1. ELECTRIC LOAD ANALYSIS

ELECTRIC PLANT LOAD ANALYSIS		02/16/98						
USCGC VINDICATOR (WMEC 3)		LOAD GROUP SUMMARY						
		MAX. CONNECTED LOAD	IN PORT	ANCHOR	CRUISE 5 kts	PATROL 7 kts	PATROL 11.5 kts	EMERG
No.	Group	KW	KW	KW	KW	KW	KW	KW
1000	DECK MACHINERY	473.9	0.0	0.0	1.0	0.0	0.0	0.0
2000	PROPULSION & STERRING	1433.3	0.0	0.0	177.3	312.3	1351.0	8.4
3000	ELEC PLANT & POWER CONV	840.2	120.3	151.9	149.2	149.2	171.9	72.1
4000	COMMAND & SURVEILLANCE	25.4	3.1	6.6	11.5	11.5	11.5	25.4
5000	AUXILIARY HOTEL	259.4	13.8	49.4	50.7	50.7	50.7	24.3
6000	HOTEL	198.4	30.5	40.9	46.7	46.7	46.7	5.7
7000	HVAC	500.1	308.8	324.4	207.4	207.4	207.4	0.0
	kW TOTAL	3730.7	476.6	573.2	643.9	777.9	1839.3	135.8
		Rating (kW)	IN PORT	ANCHOR	CRUISE 5 kts	PATROL 7 kts	PATROL 11.5 kts	EMERG
	Fuel Cell No. 1	625	1	1	1	1	1	
	Fuel Cell No. 2	625		1	1	1	1	
	Fuel Cell No. 3	625					1	
	EDG	250						1
		Rating (kW)	IN PORT	ANCHOR	CRUISE 5 kts	PATROL 7 kts	PATROL 11.5 kts	EMERG
	Fuel Cell No. 1	625	76.2%	49.5%	51.5%	62.2%	98.1%	
	Fuel Cell No. 2	625		49.5%	51.5%	162.2%	98.1%	
	Fuel Cell No. 3	625					98.1%	

2.4.3 Regulatory Requirements

ABS and U.S. Coast Guard Regulatory requirements will not be violated in the approach being considered to provide a generation plant that will have the capability of continued operation at reduced power level in the event of a single (or even multiple) fuel-cell component failure. The emergency generation plant would remain available as before.

2.4.4 Cost

An attractive cost savings can be achieved by using three fuel cells instead of four.

2.4.5 Operations

When the proposed power production capability is fully functional, the ship's current performance and operations are not compromised. However, a failure of a single unit will potentially drop the total power production to 1250 kW. This power is not sufficient for full speed operations and concurrent hotel and mission loads. Practically, top speed will be limited to approximately 9.5 knots. Regulatory requirements permit such utilization in an integrated electric propulsion plant since a minimum ship speed of 7 knots can still be sustained. However, with the current baseline design, the loss of one of four generating systems would not affect the ship's performance.

The use of the 250 kW emergency diesel generator to restore the performance to the before failure level is <u>not permitted</u> by the regulatory bodies.

2.4.6 Summary and Conclusions

As indicated in the new Electric Plant Load Analysis (EPLA), the three fuel cell units are utilized at 98.1% when the ship is operating at 11.5 knots. The system would have no growth margin that could enhance the vessel's operation in its role as a WMEC. In addition, the requirement to be able to start the largest motor while the other functional loads are on line would be compromised. Again, the emergency diesel generator is not available to complement the system.

If the USCGC VINDICATOR is to be merely a test bed for technology then the cost savings coupled with a potential degradation in ship's performance may be acceptable. Although the reliability of a fuel cell system is not clear at this time, the potential reduced top speed and the frequency of such an event occurring may still be acceptable.

If the USCGC VINDICATOR is to be an operational USCG vessel in addition to being a test bed for technology, then every effort to minimize the space required for the fuel cell power production system is required. It is too early in the design process to eliminate the option of full power afforded by a total of 2500 kW with a 4-unit system. Initially, <u>the most</u>

<u>probable application of this new technology will be in ship conversions - and space is a very limited commodity on ships.</u>

The continuation of all effort to minimize the space required for each of the four modules is required.

3.0 DEMONSTRATION FUEL CELL MODULE

This section of the report introduces the developments of the Molten Carbonate fuel cell module with an emphasis on the application of the design to a constrained marine environment. Molten Carbonate was selected as the apparent leading technology at the time. Other fuel cell concepts are feasible such as PEM. Although this impact study has been oriented toward MC, the selection of PEM technology is not expected to cause an infeasible integration problem. This section includes fuel cell module final arrangement drawings that followed four earlier developmental machinery space arrangements. The developmental work is currently proceeding, although the USCGC VINDICATOR has been pressed into active service and is not currently available for fuel cell installation. However, space and weight limitations and marine operational requirements that were uncovered through this task, are believed to be applicable for similar marine applications

3.1 Module Configuration

The configuration of the molten carbonate fuel cell power plant module along with the general location of key fluid interfaces is shown in Figure 9. The power plant configuration includes an enclosed, insulated skid-mounted module which houses the fuel cells and process equipment. This module is 7 feet-4 inches wide, 10 feet high and 17 feet-8 inches long. A step in the structural support base is provided to clear large piping in the VINDICATOR's engine room. The power plant also includes three units of electrical equipment which can be located remotely from the module. The separate electrical equipment items include: the DC to AC power conditioning system, which is 36 inches wide x 5 feet-2 inches high x 6 feet long. The motor control center, which is estimated at 32 inch x 32 inch x 6 feet high, and a 16 inch x 16 inch x 6 feet high rack for the control system with its microprocessor based process controller, and CRT interface for operation and monitoring.

The dimensions in the present design sketch are the best available estimates of the configuration at this time. The arrangement reflects design sizing of all the major components including thermal insulation allowance, and space for piping and secondary components such as control valves.

The configuration discussed in this report requires availability of desulfurized fuel (~ 100 parts per billion). The U.S. Navy is working on an on-board desulfurization plant to provide "safe" fuel for the operation of fuel cells.

A simplified schematic of the power plant process is shown in Figure 10, while a more detailed schematic of the components comprising the system at the "balance of plant" (BOP) is shown in Figure 11.

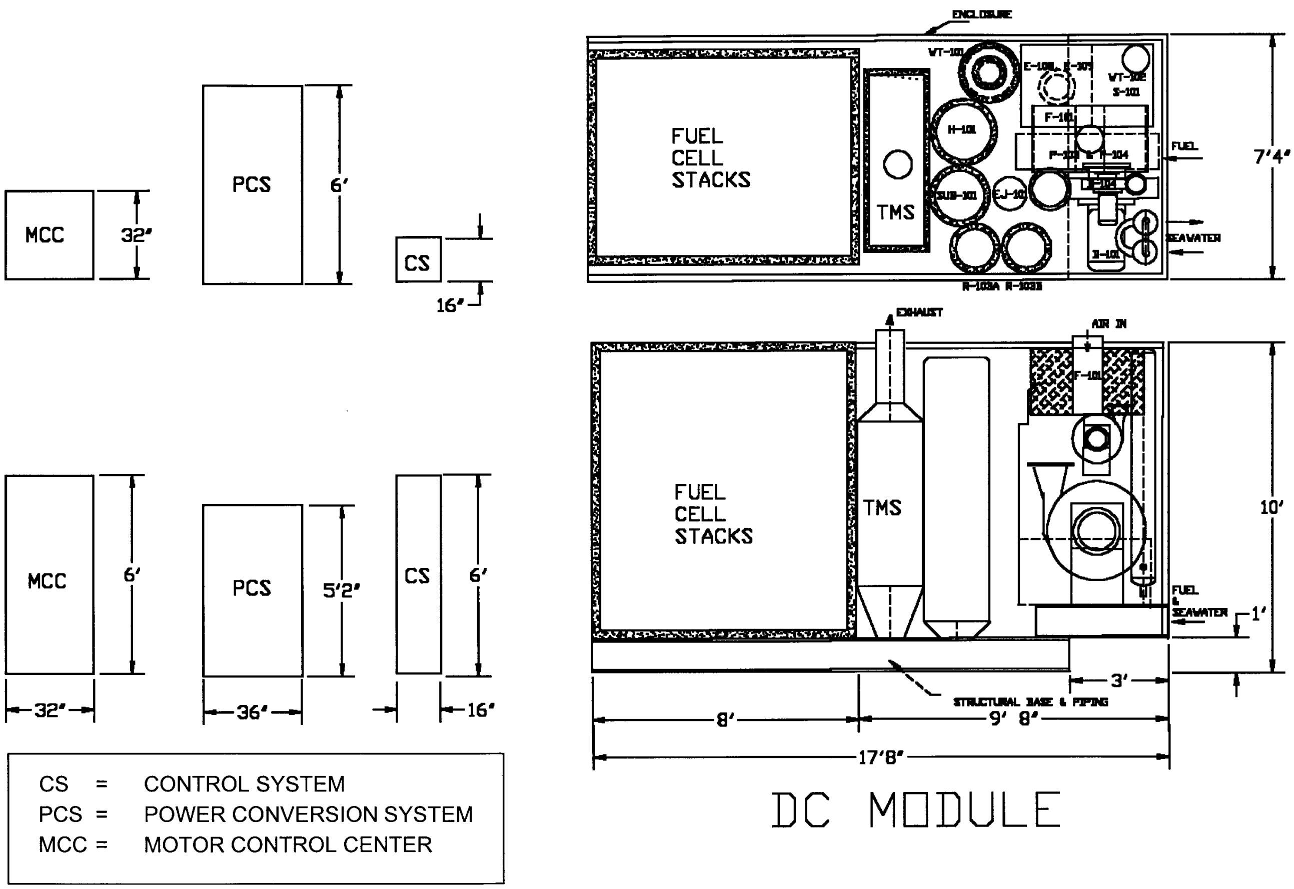


FIGURE 9. MCFC 625 kW MODULE

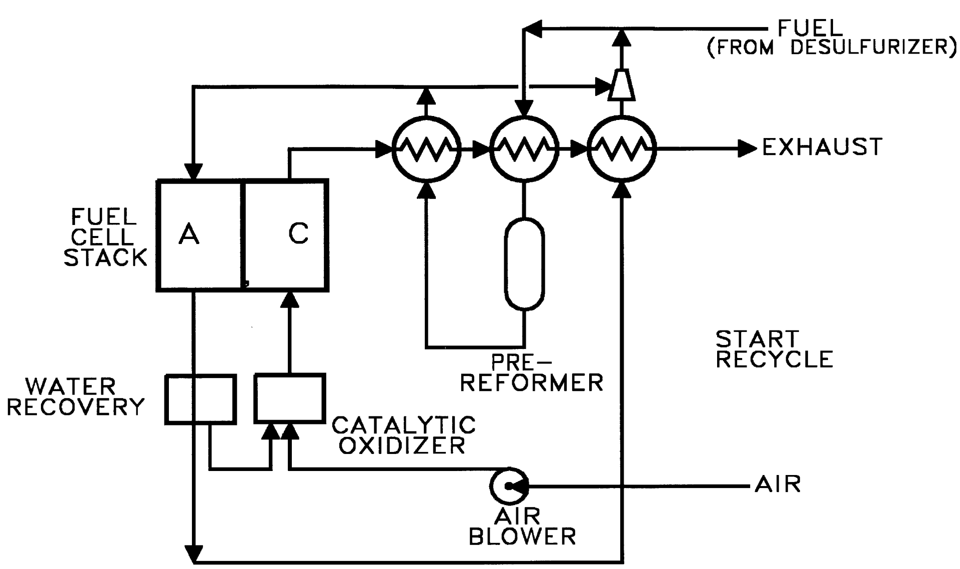
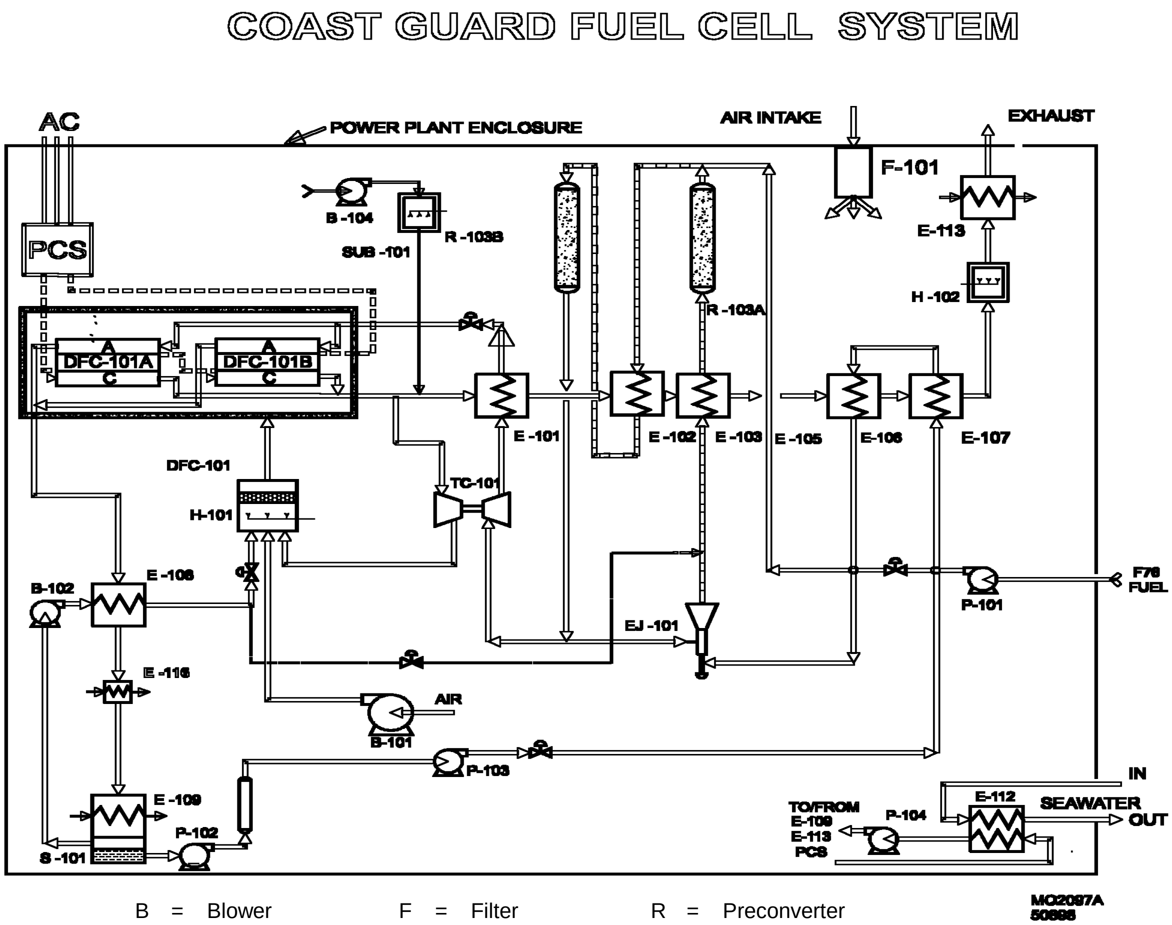


FIGURE 10. FUEL CELL POWER PLANT PROCESS (SIMPLIFIED)



B	=	Blower	F	=	Filter	R	=	Preconverter
E	=	Heat Exchanger	H	=	Burner/Oxidizer	S	=	Condenser
EJ	=	Ejector	P	=	Pump	TC	=	Turbocompressor

FIGURE 11. FUEL CELL SYSTEM AT BALANCE OF PLANT (BOP)

3.2 Commercial Parts

The design of the cell stack repeat parts is the Energy Resources Corporation (ERC) commercial fuel cell design. This was chosen in order to realize economic benefits from the commercial manufacturing facility, tooling and production rate. Standard components such as pumps and blowers are based on vendor supplied dimensions. The heat exchangers and process beds have been sized to meet process requirements. The cell stack proprietary parts and cell stack enclosure are being designed to minimize space and weight.

3.3 Maintenance Allowances

Allowances in the module arrangement have been included for piping. Except for the piping to and from the cell stack, the piping is reasonably small. For example, the fuel processing piping is only 2½ inches in diameter because of the 300 psi pressure in this part of the system. The allowances for piping are consistent with the level of design detail available at this time. The heat exchangers in the group E-101 to E-113 are packaged together and called the thermal management system (TMS), see Figure 10. H-102 is the vent management burner and is located between the E-107 and E-113 near the top of the TMS package. Large piping requirements such as for the flow between heat exchanger E-101 to E-113 in the TMS were designed into the heat exchanger packaging scheme with the cathode exhaust flow passing vertically upward through a 1 foot x 4.5 feet duct which includes the heat exchangers. A similar approach was employed in packaging E-108 and E-109 together.

Each component and its support structure, as well as the overall enclosure-structure, will be designed and analyzed to ensure the natural frequencies are outside the range of ship excitation frequencies. Also, the structure supporting the cell stacks and other parts of the module will be designed and analyzed for environmental/ship motions.

The module width and height dimensions are not expected to grow because they are established by the cell stack packaging, which is reasonably well established from the commercial fuel cell size. There could be some change in the length if more detailed design uncovers an unexpected requirement for additional space to accommodate secondary components or room for assembly or maintenance access.

3.4 Foundations

Each fuel cell module will be installed over the existing tank top on existing 9-inch longitudinal beams. The fuel cell enclosure will be mounted rigidly to those beams. Vertical flexibility will be provided within the module by using flexible piping where necessary.

4.0 PROCESS DESCRIPTION

As shown in the simplified schematic of the power plant process Figure 10, desulfurized fuel delivered to the power plant from the ship is mixed with steam, heated, and flows to a prereformer in which the Marine Diesel Fuel is converted to methane and hydrogen. The USCG MCFC is not designed with an onboard desulfurization system. Part of the converted fuel stream is recycled by a steam driven ejector. The remaining converted fuel is heated further and flows to the anodes in the fuel cells. There the methane is converted to hydrogen, and the hydrogen reacts electrochemically, producing DC current. A portion of the unreacted hydrogen, together with water formed in the cells and CO_2, flows from the anodes to a water recovery subsystem where the water is recovered for later use. This process makes the plant independent of a continuous water supply from the ship. The recovered water flows to a boiler where steam is formed for use in the recycle ejector and use in the conversion of the diesel fuel.

Process air is supplied by a blower to a catalytic oxidizer, where it is heated in reaction with the excess fuel from the fuel cell anodes. The stream from the catalytic oxidizer then flows to the fuel cell cathodes where the oxygen in the air and the CO_2 from the anodes is used in fuel cell electrochemical reaction.

A more detailed schematic of the power plant is shown in Figure 11. Interfaces include the desulfurized F-76 or Navy distilate fuel supply, the air intake from the ship, the exhaust to the ship, sea water for cooling and the AC power output converters.

The desulfurized fuel delivered to the power plant from the ship is pumped in P-101 to 360 psia and mixed with steam and recycled processed gas. This mixed stream is heated in E-102 to 950° F and flows to the preconverter, R-103B. The output of the R-103B is split with half the stream recirculated by the steam driven ejector, EJ-101, through R-103A where it regenerates the catalyst. The two preconverter beds, R-103 A & B, are periodically interchanged. The remaining converted fuel flows through a turbo expander, TC-101, is reheated to about 1050° F in E-101, and flows to the anodes. The depleted anode exit stream flows through a regenerative heat exchanger, E-108, and then to a condenser, E-109, where the stream is dried to a 115° F dew point. The dried stream is recirculated by blower B-102, through the regenerative heat exchanger, and then to the catalytic oxidizer, H-101.

The recovered water flows to a water treatment system, that includes a degasifier (not shown on the schematic) which is heated by E-116, and a mixed ion exchange bed. The recovered water is then pumped in P-103 to the feedwater heater E-107 and the boiler E-106 where steam is formed for use in the recycle ejector EJ-101.

Process air is drawn into the enclosure through the filter F-101 and flows to the catalytic oxidizer H-101. The heated air, at 1050° F, then flows into the cell stack enclosure and on into the cathodes of the fuel cells. Depleted air from the fuel cell cathodes is collected in manifolds and is piped from the cell stack enclosure. Part of the cathode exhaust stream is recirculated by the turbo expander TC-101 back to the catalytic oxidizer. The remaining cathode exhaust stream, at 1180° F, flows through heat exchangers E-101, E-102, E-103, E-106 and 107. Heat exchanger E-113 cools the exhaust stream while recovering waste heat for use on the ship as needed. Cooling of the water recovery condenser, E-109, the exhaust gas cooler, E-113, and the power conditioning system is accomplished by a closed fresh water cooling system which rejects heat to sea water supplied from the ship.

4.1 Performance Verification

Supporting engineering analysis of the MCFC performance is established in the form of a steady-state heat and mass balance on the process from fuel input to DC power output. This analysis is accomplished using CHEMCAD, a commercial software package available from Chemstations, Inc., Houston TX. This commercial software package has been extended by ERC to include a proprietary model of the direct carbonate fuel cell.

4.2 Interfaces

A listing of the fluid and electrical interfaces between the ship and the power plant, as well as the interfaces between the packaged equipment which comprises the power plant, is shown in Table 2.

TABLE 2. INTERFACE CONNECTIONS

INTERFACE	FROM	TO	CONNECTION	
			Size	Type
FLUIDS				
DIESEL FUEL SUPPLY	SHIP	DC MODULE	½ in.	FLANGE
DIESEL FUEL RETURN	DC MODULE	SHIP	½ in.	FLANGE
PROCESS	SHIP	DC MODULE	10 in.	CLAMP
EXHAUST	DC MODULE	SHIP	10 in.	CLAMP
NITROGEN	SHIP	DC MODULE	½ in.	FLANGE
SEAWATERCOOLING	SHIP	DC MODULE	4 in.	FLANGE
SEAWATERCOOLING	DC MODULE	SHIP	4 in.	FLANGE
(80-100 PSIG) AIR	SHIP	DC MODULE	½ in.	FLANGE
ELECTRICAL				
AC POWER	PCS	SHIP	2000 amp	3 CABLE
DC POWER	DC MODULE	PCS	2200 amp	2 CABLE
CRITICAL POWER	PCS	CONTROL MODULE	20 amp	
AUX POWER	PCS	MCC	200 amp	
START POWER	SHIP	MCC	200 amp	
AUXILIARY LOADS	MCC	DC MODULE	TBD	DIRECT WIRE TO LOAD
CONTROL SIGNALS	CS	DC MODULE	TBD	MULTI-PIN CONNECTOR
INSTRUMENT SIGNALS	DC MODULE	CS	TBD	MULTI-PIN CONNECTOR
CONTROL SIGNALS	CS	PCS	TBD	MULTI-PIN CONNECTOR
INSTRUMENT SIGNALS	PCS	CS	TBD	MULTI-PIN CONNECTOR

5.0 SUPPORT SYSTEMS

The design of the supporting fluid systems is based on the flow requirements as provided by ERC. The design process included a ship check of the USCGC VINDICATOR. Existing pipe runs, air and exhaust ducts and auxiliary machinery components were identified and to the largest extent re-utilized for the Molten Carbonate Fuel Cell installation. A detailed ship check report was published earlier.

5.1 Air Intake System

The machinery room air intake system consists of two parallel intake systems, one port and one starboard. These systems take suction from the weather on the 01 Level and distribute it throughout the Main Generator Room (3-34-0). The Fuel Cell modules are equipped with air fans that take suction directly from the generator room. The fuel cell needs combustion air at the rate of 13,000 lb/hr/unit at maximum load. The fuel cell module is being designed to operate in a marine environment. Equipment and support structure is being designed for attitude, shock and vibration. The process is being designed to accommodate temperature extremes, humidity and salt. The key issue relevant to operation in the salt air environment is the salt entrained in the process air. The design includes a process air filter with a de-mister, which is expected to reduce salt levels to less than 1 ppm. ERC also has a test program, as part of the Navy work, to evaluate the effect of salt on the fuel cell performance.

The air filter at the top of the module is sufficient to remove dust, dirt and salt from the process air. Drawing the fuel cell process air directly from outside the ship rather than the engine room would avoid any unexpected air borne impurities which may be present from unknown sources in the engine room. However, outside air may contain high salt levels and dust. Therefore the quality of the relatively clean machinery room air of the VINDICATOR is expected to be adequate for the fuel cells.

5.2 Exhaust System

The current diesel engines exhaust through four individual 8-inch diameter exhaust pipes. There are four silencers located in the stack. The exhaust for the space is natural exhaust through the stack via protected louvered openings. Each of the exhausts of the four fuel cell modules will be routed to the existing exhaust pipes. Since there is no need for exhaust silencers for the fuel cells they will be removed to reduce back pressure.

5.3 Nitrogen System

The Fuel Cell utilizes Nitrogen gas during the start up and shut down process. Compressed Nitrogen flasks will be part of each Fuel Cell module. Piping for re-supply of Nitrogen will be provided from four replaceable flasks that are installed on the main deck. A rigid high pressure piping system between the four flasks and the port and starboard main deck allow for recharging.

5.4 Fuel Service System

The system draws fuel from either the port Fuel Oil Service Tank (3-52-4) or the starboard Fuel Oil Service Tank (3-52-3). The capacity of a fuel oil service tank is approximately 7,000 gallons. The fuel will be provided to the fuel cell through a 1¼-inch line from both service tanks. There is also a ¾-inch return line back to each service tank for any unused fuel. The load control will be designed either to affect the return rate or by controlling a variable rpm supply pump.

5.5 Sea Water Cooling System

The sea water system takes suction from the forward 8-inch seawater main forward of the diesel engines. There are also four seawater/freshwater heat exchangers located forward of the current engines. Four new motor driven pumps rated at 250 gpm at 10 psi will be added to provide coolant to each sea to fresh water heat exchanger. The fresh water is recycled within the fuel cell. The data provided by ERC for its fuel cell design called for a total of 540,680 lb/day (1053 gpm) cooling capacity. All the piping, valves and gages to support the new system will also be installed.

5.6 Fresh Water System

Each of the fuel cells requires three gallons per minute of fresh water for the process. The current fresh water generation plant consists of two 11.3 m^3/day (2985 gal/day) Nirex watermakers that are sized to service the current entire fresh water demand. The current units utilize MDG Jacket water heat for desalination. A supplemental electrical heat exchanger is installed for limited fresh water production at low powering loads. Thus the existing watermakers cannot provide the fuel cells consumption and the water will have to be generated internally by condensation. Because of space considerations it might be necessary to replace the Nirex watermakers with two Reverse Osmosis units (84 inches by 36 inches by 36 inches). The fuel cells do not provide excess fresh water to the ship system. Virtually, all the water produced in one part of the process is reintroduced within the fuel cell and consumed. A distilled water connection for the fuel cells from the ship's system is provided. This is for initial fill-up of the system as well as makeup water during normal operation.

5.7 Control Air System

The ship's service air systems consists of two electric motor reciprocating compressors rated at 20 cfm at 125 psig and one 16 cubic feet service air receiver. The ship's service air system provides compressed and dried air throughout the ship for various functions such as sea chest blow-down, the ship whistle, and tool and cleanup stations. The fuel cell control air system requires 40 standard cubic feet per minute of high-pressure, dry, oil free air for control actuators. The existing system will be upgraded to provide the capacity and cleanliness requirements.

5.8 Fire Fighting Systems in the Motor Generator Room

The present system contains Halon flooding with athwartships headers and discharge heads forward and aft of the engines' air supply, located in the starboard side locker outboard of the crews' lounge. Integrated Module fire sensors are provided within the fuel cell module. No changes in the ship's system are required.

6.0 OPERATIONS

6.1 Start-Up

During start-up, heating is accomplished by two burners, which operate on diesel fuel. The catalytic oxidizer H-101 also includes a diesel fuel start burner. This burner heats process air which in turn heats the fuel cell stacks. A separate start burner, SUB-101, also operating on diesel fuel and with its own air blower, B-104, provides heat to the heat exchangers in the string E-101 to E-107. During the heat up stage, the system is filled with nitrogen. The nitrogen is circulated through the process beds and cell stack anodes.

6.2 Stand-By

When the fuel cell stack and process beds have reached nominal operating temperatures, the plant is transitioned to a stand-by mode. In the transition to stand-by, fuel and steam flow through the process beds purging the nitrogen, and the fuel cell voltage rises to its open circuit level. The no load DC disconnect to the inverter is closed and the inverter begins commutation creating AC voltage at its output. The auxiliary power bus is then switched from external power for its internal loads. In the stand-by mode, the AC breaker is open and the power plant sustains its operating conditions by processing fuel as required by the fuel cell. This produces power for its own parasitic loads and burns diesel fuel in the start-up burner to offset heat loss and maintain required thermal conditions.

6.3 Load Application

When a signal is received from the ship operational control station, the power conditioning system synchronizes with the ship's 600 volt power bus and closes the AC breaker. The automatic load sharing feature in the inverter control then signals the inverters on other power plants connected to the bus, and the newly connected module load is ramped up while the load on the other connected power plant is decreased until all connected power plants share the load.

The inverter includes a droop control feature which senses the voltage on the 600 volts bus. As load on the bus is increased or reduced, the inverter droop and load sharing controls adjust the AC current from each connected power plant. As the inverter responds to load demand on the ship's 600 volt AC bus, the power plant fuel and steam process flow controls respond to a DC current signal. The process air flow also responds to a DC current signal but has a bias control which also adjusts the air flow to control the fuel cell stack temperature. Thermal conditions in other parts of the system are automatically adjusted to the proper levels as the power changes by flow throttling or bypass controls around the various thermal management heat exchangers. Process water is recovered as needed by controlling condenser dew point temperature in the anode exhaust condenser E-109. The recovered water is treated and pumped back to the boiler for reuse in the fuel conditioning process.

Response of the power conditioning system to changes in the ship bus load demand is virtually instantaneous. Response of the fuel cell stacks to load change, in turn, is instantaneous when there is sufficient fuel on the anodes and oxygen and carbon dioxide on the cathodes to support the electrochemical fuel cell reactions. The electrochemical fuel cell reacts as the DC current changes in response to the inverter changing AC current to the ship bus. The system process fuel, steam and process air controls are designed to respond rapidly to changes in DC current from the fuel cell stack.

6.4 Shut-Down

The power plant is normally maintained in the hot stand-by mode when not connected to the ship load bus, as described above. When shut-down is required for a maintenance action, the auxiliary power is switched to an external source. The fuel processing system is then depressurized and vented through the vent management system. The system is then purged with nitrogen. The fuel in the cell stack anodes is also purged with nitrogen, and the fuel cell stacks and system are allowed to cool. Forced cool down can be accomplished, if necessary, by circulating nitrogen with the system anode boost blower and rejecting heat in the anode exhaust condenser and using the process air blower.

6.5 Maintenance

Routine periodic maintenance requirements on the MCFC power plant are listed in Table 3. These maintenance tasks can be accomplished without shutting down the power plant. The arrangement of the components within the module enclosure reflects attention to maintenance requirements. The enclosure will have removable side panels. The fuel processing beds are located at the edge of the module where blind flange access ports are provided to vacuum out and reload the catalyst. The air filter elements can be removed after removing a side panel from the enclosure. Any routine maintenance action will be possible without removing large parts.

The only significant components that must be periodically replaced at 5-year intervals are the two cell stacks. The stacks measure 3 feet x 5 feet by 8 feet high. The center of gravity is centralized to these dimensions. The weight is estimated to be 12,000 lbs. The cell stacks will be replaced individually, not as a subassembly. The cell stack can be lifted from the top or bottom. Special lifting fixtures may be required. The fuel processing catalyst in R-103A&B is designed for replacement at 180-day intervals, assuming average power operation.

Pumps and blowers are not expected to require routine maintenance as they are expected to include sealed bearings. Any blowers which circulate hydrogen containing gas will have magnetic drives or canned motors so seal maintenance is not a concern. Pumps and blowers should be manually monitored for excessive noise and vibration. It is not expected that vibration instruments will be required.

TABLE 3. MCFC MAINTENANCE REQUIREMENTS

COMPONENT	MAINTENANCE TASK	TASK FREQ. (Months)	TASK DURATION (Manhours)	SHUTDOWN YES/NO
Fuel pump	Replace fuel filter	6	0.25	No (2 parallel filters)
Air filter F-101	Replace filter element	6	1	No
Water treatment	Replace ion exchange resin cartridge	6	2	No
Freshwater cooling system demineralizer	Replace cartridge	12	2	No
Power Conditioning System	Replace internal cooling air filter	12	2	No
UPS	Check batteries	12	2	No
— Pump and Blower	Observe noise and vibration	6	1	No
Controller	Review stored reformer data Check process control settings	12	4 8	No No

6.6 Availability

The plant is designed for a 30-year life with overhaul at 5-year intervals which includes fuel cell stack replacement. Other components receive routine maintenance such as catalyst replacement in R-103A&B at 6-month intervals.

Mean time between failure (MTBF) is expected to exceed 2000 hours based on design attention to quality components and design based on worst case conditions. It is desired that MTBF approach 5000 hours. While there is no detailed basis for the expected MTBF, this plant has the same basic process steps of fuel conversion, fuel cell operation and electrical conversion as 200 kW on site power plants. Over 50 commercial installations of 200 kW fuel cell power plants operating on natural gas fuel have demonstrated a 2000 hour MTBF as described in a 1996 Fuel Cell Seminar paper by International Fuel Cells. In addition, the estimated MTBF for the ERC 2 MW demonstration plant was estimated independently at 1385 hours with a 25-hour forced outage duration by ARINC Research Corp., Annapolis, MD, as reported in the Electric Power Research Institute (EPRI) Technical Report TR-101107, Availability Assessment of Energy Research Corporation. 2- MW Carbonate Fuel Cell Demonstration Power plant, dated September 27, 1992. In this study the shortest MTBF in the plant was 4300 hours for the digital control system. The fuel cell stack MTBF was estimated at 65,000 hours. The stack MTBF was based on statistical techniques that used 10,000 hours of failure-free fuel cell stack operation performed by ERC on a controlled basis.

While a MTBF of 1385 to 2000 hours is less than the 5000 hours desired, the availability of a plant is expected to be above 97% and the partial availability of a plant composed of 4 independent modules is expected to be acceptable.

At this stage of design and development, MTBF is not supportable. Selected industrial components such as the system pumps, blowers, controls and instruments have recommended installation and maintenance schedules to insure reliability but suppliers typically do not provide statistical MTBF data. Custom designed components such as the cell stacks and fuel processing bed catalysts are being tested to ensure understanding of performance and life related factors.

6.7 Safety Considerations

Safety issues are addressed in the design. Fire avoidance in the module is being addressed as follows. The module enclosure is swept by the process air, which will avoid the build-up of combustible gases. The module enclosure will include combustible gas detectors. If a combustible gas mixture is detected, there will be an automatic power plant shutdown and nitrogen purge of the system fuel.

The cell stack packaging concept is a "hot box" configuration. The process air leaving the catalytic oxidizer at 1050° F flows into the cell stack enclosure and then on into the cathodes. There is no fuel in this gas surrounding the cell stacks as all the anode exhaust fuel is oxidized in H-101. The process fuel on its way to the cell stack is enclosed in pipes and cell stack manifolds. Explosive gas mixtures cannot accumulate in the "hot box" because the fuel is consumed in the catalytic oxidizer and the box is continually purged by the process air stream on its way to the cathodes.

Normally the exhaust does not include any combustibles. During rapid down load transients it may be necessary to vent anode exhaust rather than flowing it to H-101. During this condition the vent management burner will be used to avoid venting combustible gas from the power plant. The function of H-102, the vent management burner, is to ensure that any fuel gases vented from the system are below combustibility limits. Gases in the exhaust stream will be monitored for combustibility. If a combustible gas mixture is detected, an igniter will initiate oxidation of the stream in the ceramic lined burner. The exhaust from the burner will be cooled by the exhaust gas heat exchanger E-113.

Crew safety from hot surfaces is addressed by the module enclosure, which has a thermal and acoustical insulation lining. Regulatory issues have not yet been addressed for ship service as this is a new power plant concept. However, the concept is similar to that planned for the commercial carbonate fuel cell power plant and no agency objections have been encountered for the commercial design. Marine safety organization approval of this design concept has not been addressed.

7.0 ELECTRICAL SYSTEM DESCRIPTION

The MCFC power plant electrical one line diagram is shown in Figure 12. As indicated above, the power plant is rated at 625 kW net output, delivering 3-phase 60 Hz power at 600 volts. The power plant has about 30 kW of parasitic load for pumps and blowers which is also supplied by the output of the power plant. In the power plant, DC power produced by the fuel cells is converted to AC power by the inverter in the power conditioning system.

A one-line diagram of the inverter is shown in Figure 13. The inverter includes a no-load disconnect switch, isolation diodes, DC capacitors, three inverter bridges, three isolation transformers and a bank of AC capacitors and Electro-Magnetic Interference (EMI) filters.

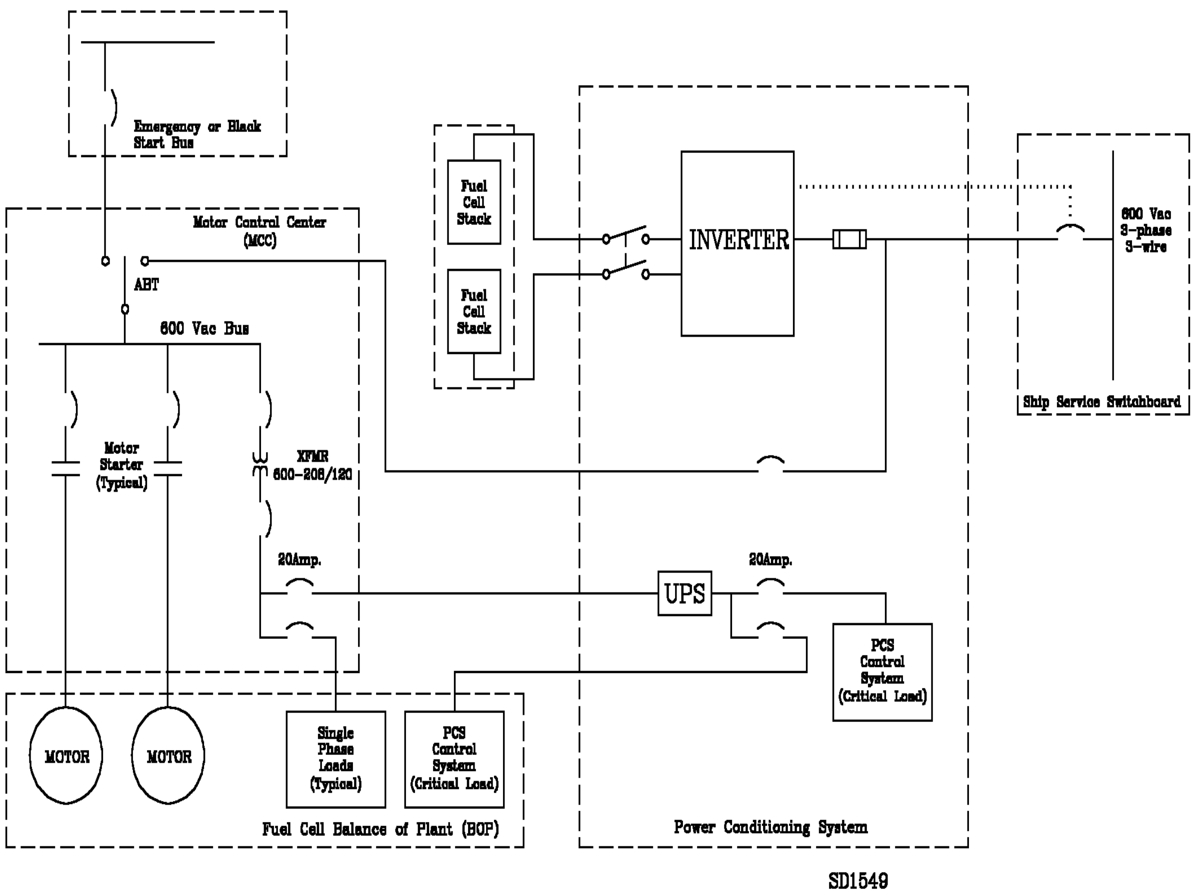


FIGURE 12. MCFC POWER PLANT ONE-LINE DIAGRAM

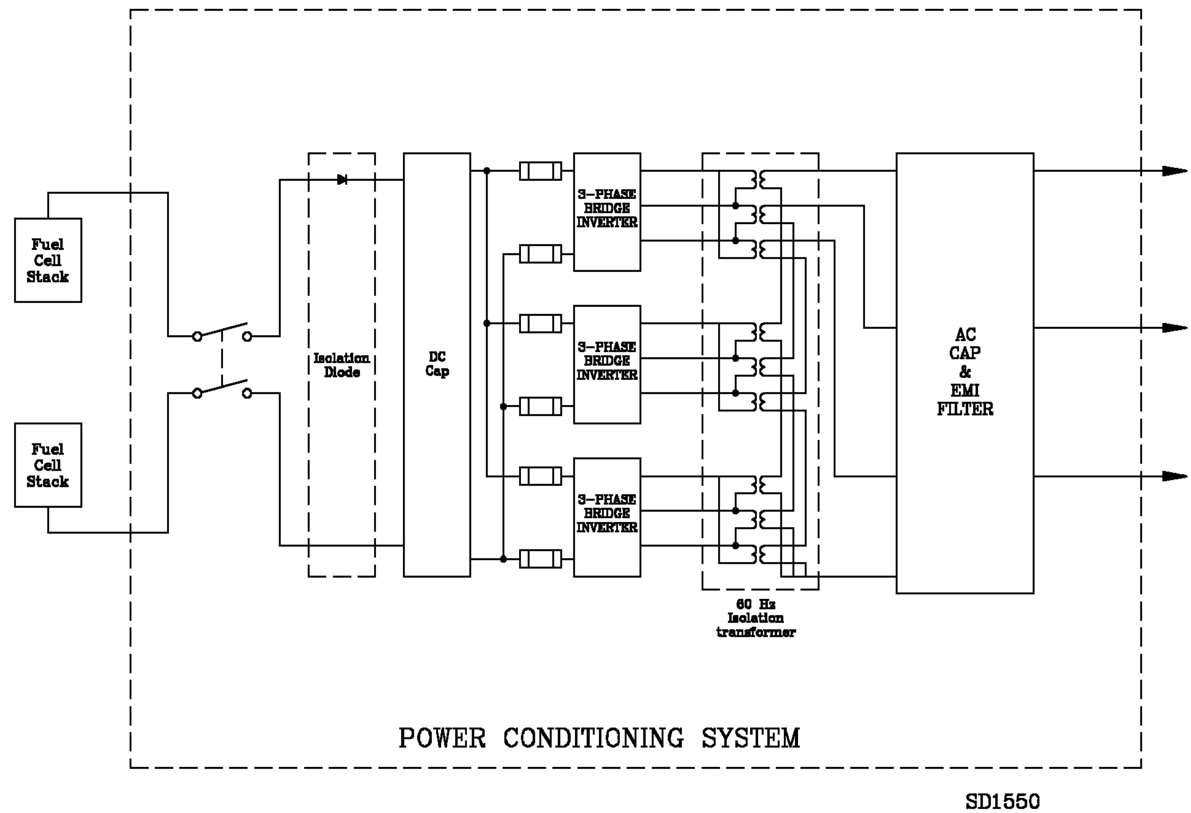


FIGURE 13. INVERTER ONE-LINE DIAGRAM

The power conditioning system includes provision for automatically sharing load on the output bus with other connected power plants. This is accomplished by an auto synchronization and bus voltage droop control.

The carbonate fuel cells in the MCFC are grouped in two stacks, which are electrically connected in series and have reactants distributed to them in parallel. The stacks are packaged within an insulated enclosure, which is swept by the incoming cathode reactant stream.

7.1 Power Output

The electrical power output as well as the parasitic loads, the gross AC output, and the DC power generated by the fuel cells are summarized in Table 4.

7.2 System Efficiency

Table 4 shows the DC and the gross AC power at partial and full load conditions. The efficiency of the over all power plant as a function of load is shown in Figure 14. Efficiency is defined as the net AC power output divided by the energy of the fuel input which is the fuel flow times the fuel lower heating value (LHV). This efficiency accounts for losses in the power conditioning system as well as the parasitic losses for the pumps and blowers in the system.

TABLE 4. POWER RATINGS

CONDITION	DESIGN	RATED	75%	50%	35%	25%	10%
NET AC POWER, kW	625	625	469	313	219	156	62.5
PARASITICS, kW	30	30	24	18	14	12	10
GROSS AC, kW	655	655	493	331	233	168	73
FUEL CELL DC, kW	690	690	524	355	251	183	80

The net lower heating value efficiency of the power plant over range of power from 10% to 100% is shown in Figure 14. The efficiency is 50% or greater over the range between 36% and 70% power. At 10% power, the efficiency is still above 40%. This efficiency characteristic suggests that when multiple power plants are installed, as in the case of the VINDICATOR retrofit, it is more effective to have all power plants operating simultaneously.

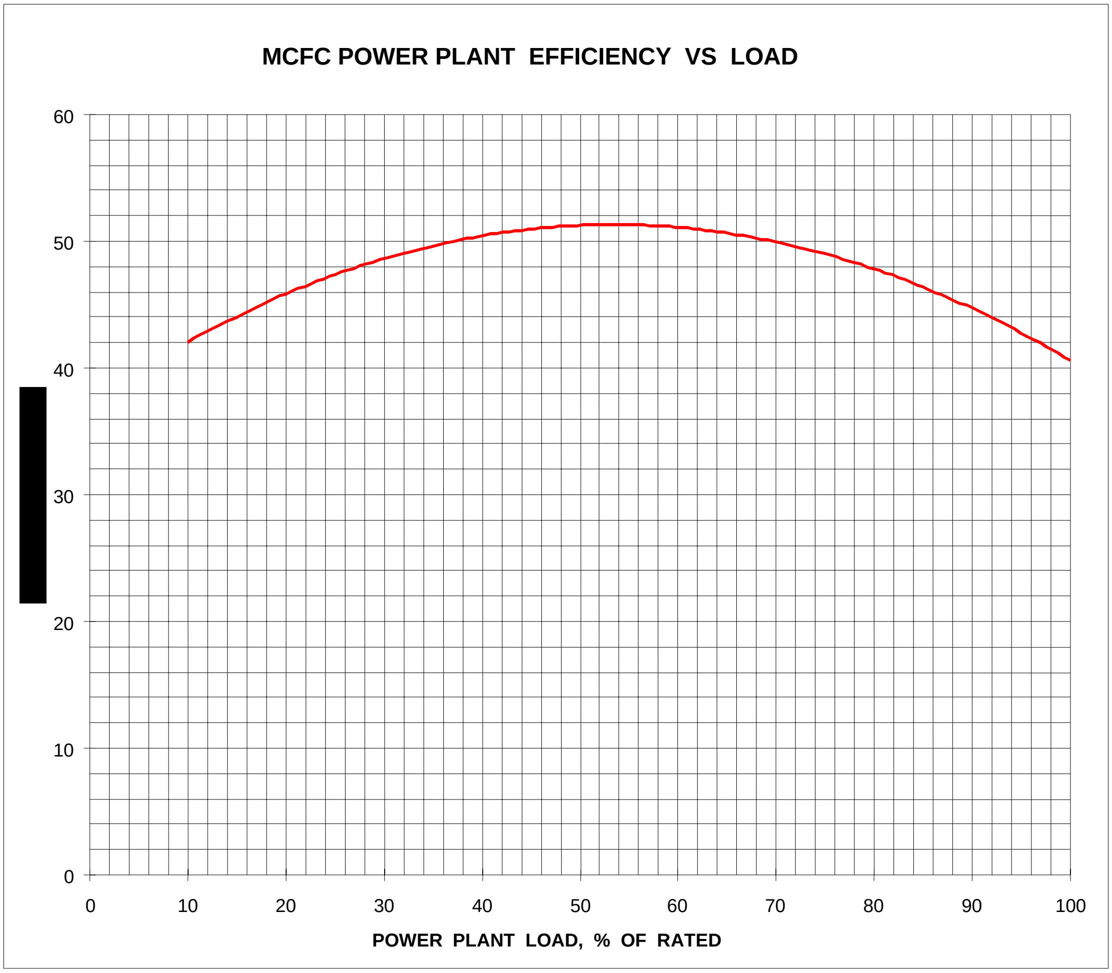


FIGURE 14. MCFC POWER PLANT EFFICIENCY VERSUS LOAD

A listing of the power plant parasitic loads is presented in Table 5. The air blower constitutes about three-quarters of the parasitic power load.

TABLE 5. FUEL CELL POWER PLANT, 625 kW MODULE, PARASITIC POWER REQUIREMENTS

ITEM	**PARASITIC POWER, kW**
AIR BLOWER	23
DIESEL FUEL PUMP	0.4
CONDENSATE PUMP	0.2
BOILER FEED PUMP	1.5
ANODE RECYCLE BLOWER	1.5
FRESH WATER COOLING PUMP	2
UPS	0.2
CONTROLS	1
MISCELLANEOUS	0.2
TOTAL	**30**

8.0 SIMULATION

The following section reports the status of the dynamic simulation effort to-date. A flow diagram describing the components and the interfaces with ship systems involved in the electro-chemical process was provided by ERC. JJMA's effort is concentrated on integration of the fuel cell mechanism to the ship's load centers and users. A mathematical model of the VINDICATOR and her propulsion system was developed by JJMA, while the mathematical dynamic performance description of the fuel cell components was developed by ERC.

8.1 Models

Utilizing the SIMSMART simulation program, the fuel cell internal piping was modeled and interfaced with the ship's support system, fuel, seawater and exhaust.

A mathematical model of the ship, the propulsion motors and the fixed pitch propellers was developed and tested. Implementation of these models into SIMSMART is currently underway.

8.2 Fuel-Cell Power Output Response

In addition to providing the quantity of power required, the MCFC will be required to respond to the demands caused by the changes in the electric plant loading. This will require the MCFC to mimic the response capability of the existing diesel generator sets and will require the MCFC control system to respond in similar time constraints as the diesel generator configuration. The guidelines to which this is to be accomplished are derived from DOD-STD-1399 or the IEEE-STD-45 equivalent, which provides the alternating current power characteristics for shipboard power systems.

The present control system employs an "Anti-Blackout" circuit which acts as a limiting device which electronically reduces the throttle signal of the propulsion and bow thruster throttles should the demand for electric power be more than what can be supplied at any one time period. This is active no matter how many generators are on line, and this approach will apply also to the newly installed MCFC units, the generator replacements.

9.0 SIMULATION TOOLS

This section provides a summary of a literature search of available simulation tools for prediction of fuel cell performance. It presents both the Steady State Simulation tools and Dynamic Simulation tools that have been identified. The Dynamic Simulation tools review has been extended to include programming tools that can integrate the fuel cell with the shipboard support systems and propulsion hardware that enable the simulation of shipboard realistic time dependent loading conditions.

There is no readily available commercial simulation tool that can be utilized without significant modifications and programming additions to provide the dynamic simulation of a marine propulsion and power system utilizing fuel cells. The current effort was concentrated on adapting a commercial simulation tool, originally dedicated to fluid systems simulation, to a tool capable of dynamic simulation of an integrated marine power system.

An earlier report by JJMA, “Review of Simulation Tools Report” dated July 31, 1998, depicts and compares an extensive list of commercially available software tools and provides examples.

9.1 ERC’s Experience In Steady-State and Dynamic Simulation

- Integration of fuel cell model with CHEMCAD (Chemstation Inc., Houston, TX) simulation software
- Integration of fuel cell model with Aspen_plus simulation software (Aspen Technology, Inc., Cambridge, MA). This work was performed in collaboration with FDI (Fluor Daniel Inc., Irvine, CA)
- National Science Foundation (NSF), 1996, intelligent control and dynamic simulation of carbonate fuel cell power plant as distributed generation systems. Developed dynamic simulation of natural gas fuel cell system using MATLAB.
- DOE cooperative agreement, 1995, development of dynamic simulation model for direct fuel cell commercial power plant. Developed DSM for natural gas fuel cell system (ERC/FDI) using speed-up simulation software.
- ERC’s in-house research and development (IR&D), 1995-96, DSM for Santa Clara Demonstration Project (SCDP). Developed dynamic simulation of the fuel cell module using MATLAB.

9.2 Other DSM Efforts On Carbonate Fuel Cell Systems

- A dynamic simulator for a 250 kW class external reforming-MCFC system, ECN and Bradstofcel, Nederland. (Limited information). The simulation software is Protrax (Trax Corporation, Forest, VA).
- Dynamic modeling and control of molten carbonate fuel cell systems. Delft University of Technology, 1994. The simulation software used is Speedup (Aspen Technology, Cambridge, MA).

9.3 Commercially Available Dynamic Simulation Systems

The following are simulation tools with specialized orientation that can be utilized to investigate various aspect of a fuel cell power generating system.

9.3.1 Process Oriented

- Speedup - Aspen Technology, Cambridge, MA
- Hysis - Hyprotech, Calgary, Canada
- Protiss - Simulation Sciences Inc., Brea, CA (Not PC-based)

9.3.2 Control Oriented

- MATLAB - The Mathworks, Inc., Natick, MA
- ACSL - MGA, Concord, MA
- Specialized (Power Plant Oriented)
- MMS - Developed by EPRI and Babcock & Wilcox, managed by MGA, Concord, MA.
- Protrax - Trax Corporation, Forest, VA.

9.4 JJMA - Dynamic Simulation Tools

JJMA developed the DSM using SIMSMART™, MATLAB, and VISUAL BASIC. The functional relationships and associated time rate derivatives for the fuel cell were provided by ERC. These were integrated with the BOP comprising of the ship's auxiliary fluid systems and with newly developed software that depicts the propulsion system components and the hydrodynamics of the propeller and the vessel.

9.4.1 SIMSMART

SIMSMART is a family of fully integrated, object-oriented, real-time tools used for process simulation, HVAC simulation, discrete/packaging simulation, plant and ship systems modeling, process modeling and simulation. SIMSMART allows the user to visualize how systems or processes will behave in real-time or faster than real-time environments. SIMSMART permits users to model, design and evaluate, dynamically test and confirm engineering data. SIMSMART is a real-time, physics-based simulation software package used to design, optimize, and maintain new and existing marine and industrial systems and processes. It is a powerful tool that allows the user to:

- Simulate distributive systems such as: compressible and incompressible fluid flow, and HVAC
- Create schematic on-screen representations of system operations with real-time response
- Quickly modify operating parameters and receive immediate results as

they would be received from the real system

- Run simulations faster than real-time to monitor a process that may take a full day, in less than 1 hour
- Examine many alternatives in a short period of time, optimizing both design cost and system performance; and
- Identify design problems in advance of construction.

9.4.2 Dynamic System Simulation Models

JJMA utilizes real-time, dynamic system simulation models via SIMSMART software on both the Silicon Graphics (UNIX) and Windows NT platforms to support a large number of engineering tasks in shipboard life cycle design, including:

- Conduct System Concept and Trade-Off Studies
- Simulate System Operations
- Demonstrate Compliance with Specification Requirements
- Perform Flow Network Analyses (FNA)
- Support System Operator Training
- Conduct Life-Cycle Studies
- Conduct Life-Cycle Studies.

9.5 Simulation Tools for the MCFC and for the Supporting Auxiliary Systems

As stated above, there are numerous commercial dynamic simulation software packages in the market today. Many of these simulation software packages cater to one specific application such as process control, aviation, or mechanical design. A few software packages provide a general-purpose dynamic simulation platform with additional strength in specific areas.

As an intermediate step, a stand alone program was created to simulate the performance of the preconverter and the fuel stacks. The user interactive program is written in VISUAL BASIC and provides the time record from a power demand instruction to the provision of the power. Graphic results such as time records for gas components concentration are created using Microsoft EXCEL. The stand alone program is translated into a C language subroutine which is integrated with the BOP (Balance of Plant) model comprising the ship's auxiliary fluid systems and with newly developed software that will depict the propulsion system components and the hydrodynamics of the propeller and the vessel.

10.0 MCFC DYNAMIC SIMULATION

In this section, an overview of the principles of the MCFC power plant operation and its interface with the ship electrical distribution system is described. In order to simplify the task of dynamic simulation modeling, the MCFC power plant is decomposed into major operational blocks. The interactions between the operational blocks are described. A simplified model of the power plant operation is described and the key system variables are identified.

10.1 Overview Of MCFC Power Plant

Figure 15 shows a simplified block diagram of the MCFC power plant including the overall organization and inter-relationships of the key electric/control components and the power and information signal flows. As shown in Figure 15, the major components consist of:

- Fuel Cell direct current (dc) Block
- Power Conditioning System (PCS)
- Control System (CS)
- Motor Control Center (MCC)

The Fuel Cell DC Block is the key component responsible for generation of power. It may further be broken down into two major subsystems: Fuel Cell and Balance-of-Plant (BOP). The BOP is responsible for providing the suitable gases to the anode and cathode of the Fuel Cell and receiving and processing the anode out and cathode out streams from the Fuel Cell. Major components of the BOP are: Distillate Marine Diesel Fuel (DFM) fuel processing, water recovery subsystem, and heat recovery units. The rotating components for delivering air and fuel are also part of the BOP, but are shown as separate units in Figure 15.

The PCS is primarily responsible for the conversion of direct current (DC) produced by the fuel cell to alternating current (AC). The PCS mainly consists of inverters, AC switch gear, DC no-load disconnect switches, isolation transformers and internal control system. The DC-to-ac inverter is the key component of the PCS and is responsible for producing 600 Vac, 3 phase 60 Hz AC power from the DC source efficiently and with minimal harmonics. The semiconductor device considered currently for the MCFC inverter is IGBT (Insulated Gate Bipolar Transistor). The PCS also performs the automatic load control for balancing between the fuel cell modules in the power plant.

The Control System (CS) functions as master system controller and provides for the coordination of the power plant subsystems and decision making tasks. All the Fuel Cell DC Block process control and data acquisition tasks are performed by the CS. It also performs the regulatory control between the PCS and the Fuel Cell DC Block and sequencing between operational states.

The MCFC power plant is designed to carry its own auxiliary load and has idling capabilities. The auxiliary power to the plant is provided by the PCS through a Motor Control

Center (MCC). The MCC provides the on-and-off switching for starting the motors for the blowers and pumps in the power plant. It also houses the variable speed controls for certain blowers and step-down transformers for 600-208/120 Vac circuits.

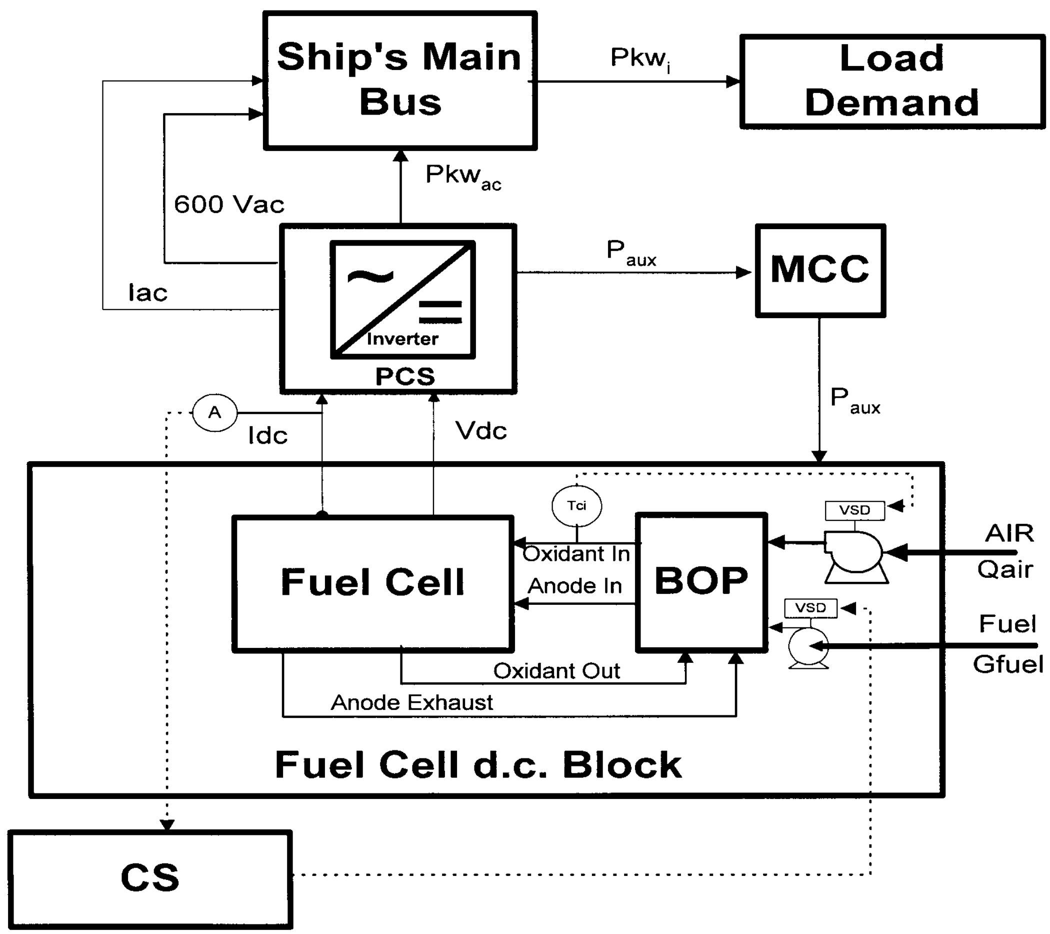


FIGURE 15. MCFC POWER PLANT POWER CONTROL DIAGRAM

10.2 Overview Of The MCFC Power/Control Strategy

During all operating modes, the CS will provide the coordination and control required for fuel flow, steam flow, fuel utilization, process temperatures and pressures, and electric power load generation. The amount of power/current that can be drawn from the fuel cell is directly proportional to the concentration and flow of reactants (H_2, CO, CO_2) within the fuel cell stacks which are continuously monitored and controlled by CS.

On a vessel, the load demand from various equipment, Pkwi, would cause the ship's main bus to draw a power of Pkwac from the PCS as shown in Figure 1. Under all circumstances of load ramp up or down, the PCS will try to maintain a constant voltage, Vac, equal to 600 Vac on the ship's main bus by varying the DC current, Idc. The PCS would pump more current, Iac, in case of power ramp up and puts out less current during power ramp down.

Simultaneous to providing Pkwac power to the ship's main bus, the PCS also provides for power plant's auxiliary power demand, Paux. The net effect of changes in power demand and/or auxiliary power consumption is a change in DC power drawn from Fuel Cell DC Block, Pkwdc. The response of the PCS and its inverter to the AC load change is quite fast and maybe assumed instantaneous for this study. The response of the fuel cell stack to changes in power demand is in the order of micro-seconds and can be considered to be instantaneous.

As the DC power demand from the fuel cell increases, Idc will increase and Vdc decreases. The interdependency of Vdc and Idc is governed by the fuel cell type and design. The DC current, Idc, is an important control variable in the power plant operation.

The control system for the MCFC must be designed to provide two major process system management functions:

a. Adjusting the fuel flow to the fuel cell to produce the desired fuel cell power output and fuel utilization. The CS regulates the fuel flow to fuel cell by measuring the DC current from DFC and provides a set point for fuel utilization.

b. Control of oxidant gas (passing through the cathodes) in order to maintain the fuel cell stacks within their required operating temperature regimes. The plant control system functions, which are required to provide this capability, are control of oxidant gas temperature either at the cathode inlet (Figure 1) or the cathode outlet. The manipulated variables for the control of temperatures at the cathode inlet (or exit) are the air flow to MCFC (Figure 1) and supplemental fuel to either start-up or main burners.

The BOP dynamic response to load change is critical in determination of the power plant transient behavior. As a first step the analysis assumed a fast response from certain BOP equipment such as fuel processing reactors, pumps or heat exchangers.

10.3 Dynamic Simulation Model Of The Fuel Cell DC Block

Fuel cells by themselves are very quick in responding to outside stimuli if the reactants (anode and cathode gases) are delivered promptly. The most important factor in DSM is to formulate the fuel processing response characteristics. The key equipment in the fuel processing subsystem is the preconvertor. Figure 16 shows a schematic block diagram of the fuel cell and preconvertor. The guidelines for the modeling of the preconvertor and the fuel cell are described in the next sections.

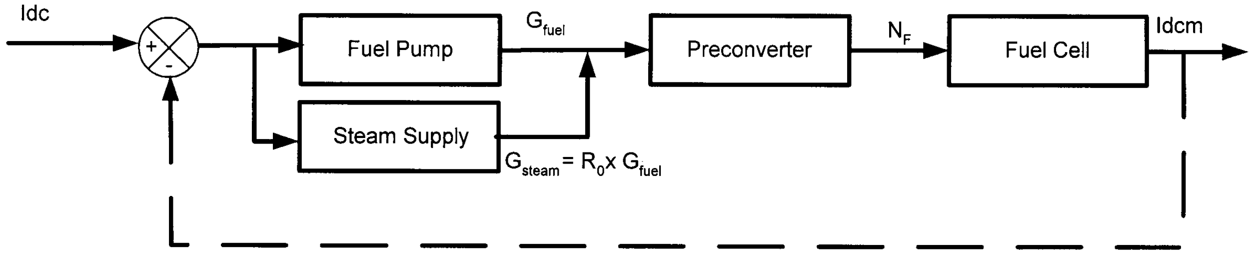


FIGURE 16. FUEL CELL AND PRECONVERTER SCHEMATIC BLOCK DIAGRAM

10.4 Preconverter Model

The pre-converter functions as a pre-reforming step for converting higher hydrocarbon feedstock to hydrogen and methane rich gas suitable for usage in Direct Fuel Cell. The feedstock to the pre-converter is DFM. The temperature level in the pre-reformer is 450°C to 520°C. The chemical reactions proceeding in the pre-reformer are listed below:

$$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)H_2 \qquad (1)$$

The catalytic steam reforming of methane described by

$$CH_4 + 2H_2O \Leftrightarrow CO_2 + 4H_2 \quad \text{Reforming Reaction} \qquad (2)$$

And, a second reaction, gas-water shift reaction, converts the carbon monoxide to hydrogen

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad \text{Gas-Water Shift Reaction} \qquad (3)$$

Reaction (1) is irreversible and the higher hydrocarbons are almost completely converted into CO and H_2 at the steady state conditions. The shift (equation 3) and methanation (equation 2) reactions are assumed to be quickly equilibrated and simultaneously taken place with the reforming reaction. The steam reforming reaction of the higher hydrocarbons (Equation 1) dominates the dynamic response of the pre-converter.

10.5 Fuel Cell Model

The Direct Fuel Cell (DFC) utilized in the USCG MCFC power plant is based on ERC's internal reforming carbonate fuel cell technology. In DFC design, the steam reforming of hydrocarbons such as methane is performed internal to the fuel cell. Consequently the hydrogen required for fuel cell operation is directly produced from hydrocarbons supplied to the DFC without the need for an external reformer. The governing equations describing the electrical current generated by the fuel cell must reflect the hydrogen production rate by the internal steam reforming.

DFC consists of a multi-cell stack of individual fuel cells. Each cell consists of an anode and cathode, separated by a porous ceramic matrix filled with carbonate electrolyte. The reforming catalyst is strategically placed both in the anode gas flow field and special individual reforming units inside the fuel cells. The catalytic steam reforming of methane inside the fuel cell follows the same reforming reaction and gas – water shift reaction as described in (2) and (3). The hydrogen, H_2, is oxidized in the fuel cell anode by carbonate ions (CO_3) by way of the reaction:

$$H_2 + CO_3^{=} \xrightarrow{anode} H_2O + CO_2 + 2e^- \qquad (4)$$

The oxygen and carbon dioxide present in the oxidant stream are reacted in the cathode to form $CO_3^{=}$ ions as follows:

$$\tfrac{1}{2} O_2 + CO_2 + 2e^- \xrightarrow{cathode} CO_3^{=} \qquad (5)$$

The net electrochemical reaction generating electricity is resulted via the above two reactions:

$$H_2 + 1/2\, O_2 \rightarrow H_2O + CO_2 + \text{Electricity (Direct Current)} \qquad (6)$$

The DC current produced is proportional to the extent of the above electrochemical reaction in accordance with Faraday's Law. There are also process time delays associated with the flow of material and energy in MCFC system. For example, with the physical movement of a fluid as it is transported through a pipe, the *transportation time (dead time)* would be equal to the length of pipe divided by the fluid velocity. The DSM of MCFC will utilize the appropriate time delays, t_L, for the oxidant delivery subsystem, heat recovery units, fuel pump and other major pipes and valves in the system. These parameters will be incorporated during the coding and detail programming phase of the DSM.

10.6 Load Demand Simulation

The realistic evaluation of the electric load demand for VINDICATOR requires consideration of the primary elements of the integrated electric power plant. These elements consist of the AC ship service loads and the AC/DC propulsion loads, both of which are fed from a common power bus. While the largest demand load elements are the propulsion loads associated with the 800 hp propulsion motors, the transient response characteristics of the propulsion system acting alone does not place the most stringent response requirements on the power source. This is due to the hull form design characteristics and the inherent load limiting capability of the propulsion drive controllers. Simulation of the ship maneuvering characteristics such as forward acceleration and crash stops provide rate-of-change time constants that should be acceptable to the ship operator, and are relatively slow with respect to power source transient demands. The propulsion load demand, which includes the hull resistance and inertia characteristics, including the shafting, propulsion motors and the propeller four quadrant characteristics, was simulated even though it does not represent the most stringent operating requirement for the power source.

The second element of the electric load demand consists of the aggregate loads of the constant voltage, constant frequency ship service power system. This element, acting alone while the ship is in port or at anchor, or in combination with the propulsion loads at sea, must comply with the electrical distribution system interface characteristics, to ensure acceptable operation of shipboard electrical and electronics equipment. The electrical distribution system interface characteristics are as described in DOD-STD-1399 Section 300, IEEE-STD-45, and Classification Society Rules. This element places the most stringent demand response characteristics on the power source as expressed by the requirements of MIL G-21410A for the governing systems and MIL G-21296B for generator sets. Tightly controlled transient voltage and frequency variations and rapid recovery times are mandatory for successful system operation. An excerpt from the applicable IEEE specifications is as follows:

A. **IEEE Std 45 – 1998: 5.6 PRIME MOVERS**

Each prime mover should be fitted with an efficient speed regulating governor as well as an automatic overspeed trip. The automatic overspeed trip should function to shut down the unit automatically when the speed exceeds the designed maximum service speed by more than 15%. The overspeed trip should also be equipped with a means for manual tripping. Each prime mover should, in addition, be under control of an efficient operating governor capable of limiting the speed, when full load is suddenly removed, to at least 5% less than that of the overspeed trip setting. The prime mover and regulating governor should also limit the momentary speed variation to 5.5% of the rated speed when 75% of the rated load of the generator is suddenly applied followed by the remaining 25% after an interval sufficient to restore the speed to steady state. The speed should return to within 1% of the final steady-state speed as follows:

Load	Response time	Speed deviation
±75%	2.0s	5.5%
±100%	5.0s	7.5%

Emergency generator sets should accept 100% rated kilowatt load in one step. All sets of 100 kW capacity and above should be provided with a coupling fitted to the rotor or armature shaft.

Each generator should be driven by a separate prime mover that, if used to drive other auxiliary loads, should have sufficient capacity for the total load, unless it is not possible to use the generator and the other auxiliary load simultaneously. Generating sets that operate in parallel should be provided with a switch that trips the generator circuit breaker when the overspeed device is actuated. . .

B. **IEEE Std 45 – 1998 4.5 AC POWER SYSTEM CHARACTERISTICS**

Power distribution systems should maintain the system characteristics described in Table 4-1 under all operating conditions. Power-consuming equipment should operate satisfactorily under the conditions described in Table 4-1, and should be designed to withstand the power interruption, transient, EMI, RFI, and insulation resistance test conditions inherent in the system. Power-consuming equipment requiring a non-standard voltage or frequency for successful operation should have integral power conversion capability. Power-consuming equipment should not have inherent characteristics that degrade the power quality of the supply system described in the following Requirement Table.

C. IEEE Std 45 – 1998 REQUIREMENT TABLE

Characteristics	Limits
Frequency	
a) Nominal frequency	50/60 Hz
b) Frequency tolerances	±3%
c) Frequency modulation	•/2%
d) Frequency transient;	
1) Tolerance	±4% 2s
2) Recovery time	
e) The worst-case frequency excursion from nominal frequency resulting from b), c), and d)1) combined, except under emergency conditions.	±5 '/2%
Voltage	
a) User voltage tolerance:	
1) Average of the three line-to-line voltages	±5% ±7%
2) Any one line-to-line voltage, including a)1) and line voltage unbalances b)	
b) Line voltage unbalance	3%
c) Voltage modulation	5%
d) Voltage transient:	
1) Voltage transient tolerances	±16% 2s
2) Voltage transient recovery time	
e) Voltage spike (peak value includes fundamental)	±2500 V (380-600 V) system; 1000 V (120-240 V) system.
f) The maximum departure voltage resulting from a)1) and d) combined, except under transient or emergency conditions.	±6%
g) The worst case voltage excursion from nominal user voltage resulting from a)1), a)2), and d)1) combined, except under emergency conditions.	±20%
Waveform voltage distortion	
a) Maximum total harmonic distortion	5%
b) Maximum single harmonic	3%
c) Maximum deviation factor	5%
Emergency conditions	
a) Frequency excursion	-100 to +12%
b) Duration of frequency excursion	Up to 2 min
c) Voltage excursion	-100 to +35%
d) Duration of voltage excursion:	
1) Lower limits (-100%)	Up to 2 min
2) Upper limit (+3 5%)	2 min

These stringent requirements were not selected for simulation and modeling at this time since the molten carbonate fuel cell system design is not yet at the stage of development that will provide the required data of system characteristics and performance. Conventional generator set prime movers meet these criteria. However, most turbo-charged diesels have difficulties meeting the criteria. Ultimately, the transient response characteristics of the existing diesel generator sets and the proposed fuel cell system must be similar to ensure system performance that is in full compliance with the interface standards.

Simulation of ship's maneuvering such as forward acceleration and crash stop provide time rates that if acceptable to ship operators, can be used by the designers of the fuel cell. The very short transient requirements can be met by energy accumulators designed into the system.

The current load demand simulation includes the vessel's resistance and inertia characteristics, the shafting including the propulsion motors and the propeller's four quadrant operational characteristics.

As discussed above, the full compliance with IEEE-STD-45 or equivalent DOD requirements need not be thought of as a project limitation for the application of FC in the marine industry as it is a solvable problem. The selection of an over sized diesel generator is often the selected solution for non-compliance of advanced diesel generators. Load shedding and power accumulation are some of the ways to enhance the transient response of the FC.

10.7 Support Ship Systems Simulation

10.7.1 Air Intake System

The machinery room air intake systems take suction from the weather. The Fuel Cell modules are equipped with air fans that take suction directly from the machinery room. The fuel cell needs combustion air at the rate of 13000 lb/hr/unit at maximum load. The detailed simulation will include the MCFC's dedicated air supply fan and ducting. Air supply demand is calculated but the actual supply will initially not be controlled.

10.7.2 Exhaust System

Each of the exhausts of the fuel cell modules is routed to the existing remaining exhaust pipes. The detailed simulation will include the MCFC's exhaust ducting leading from the fuel cell to the atmosphere including the waste heat exchangers utilized to reform the fuel and to reduce exhaust temperature.

10.7.3 Fuel Service System

The system takes suction from either the port Fuel Oil Service Tank (3-52-4) or the starboard Fuel Oil Service Tank (3-52-3). The capacity of the fuel oil service tank is approximately 7,000 gallons each. The fuel is provided to the fuel cell through a line from both service tanks. There is also a return line back to each service tank for any unused fuel. The load control will be designed either to affect the return rate or by controlling a variable rpm supply pump. The simulation includes the fuel tank, fuel supply pump and the piping leading through reformers to the fuel cell.

10.7.4 Sea Water Cooling System

The sea water system takes suction from the forward seawater main forward of the diesel engines. New motor driven pumps rated at 250 gpm at 10 psi will provide coolant to each sea to fresh water heat exchanger. The fresh water is recycled within the fuel cell BOP at a total of 540,680 lb/day (1053 gpm) cooling capacity. The simulation includes the seawater pump and the piping leading through a fresh water heat exchanger.

10.7.5 Fresh Water System

Each of the fuel cells requires three gallons per minute of fresh water for the process. The simulation model includes the internal fresh water system as part of the BOP simulation.

10.8 User Interfaces

Execution of the simulation requires the use of two computer programs to execute the simulation. SIMSMART the commercial program that was selected by NAVSEA for fluid systems simulations is the principal tool that runs the DSM. Excel, Microsoft's spreadsheet program, is used for "trend" presentations. Also the BOP presentation is attached to this report, in a larger scale. The icons for the ship, the electric motors and the fuel cell are integrated between the various segments of SIMSMART.

Input to SIMSMART is interactive. Example of parameters and variables can be seen on computer screen images shown in Figures 17 through 22. Figure 17 shows SIMSMART screen of the Balance of Plant (BOP). Figure 18 is a selected close-up about the Fuel Cell in Figure 17. Figure 19 is a SIMSMART screen showing a simplified system with ship model and electrical motor simulation variables. Figure 20 is a SIMSMART screen that shows a close-up of the ship and fuel cell with the Run-Time Data Access pull down menu. Figure 21 is an enlargement of the Run-Time Data Access pull down menu and Figure 22 is an enlargement of the ship model and electrical motor simulation variables seen in Figure 19. Selected results at time steps through the simulation are dumped into output files that are retrieved into Excel spreadsheets for customized presentations as seen in Figures 23 and 24.

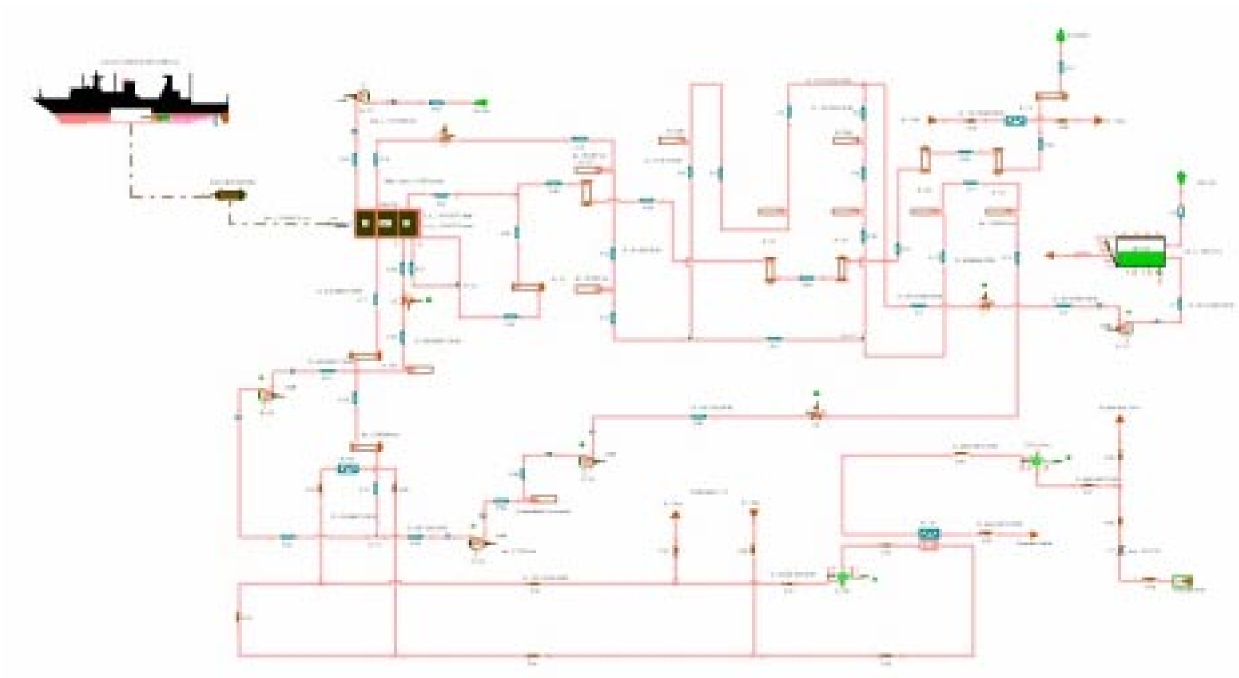


FIGURE 17. SIMSMART SCREEN – BALANCE OF PLANT

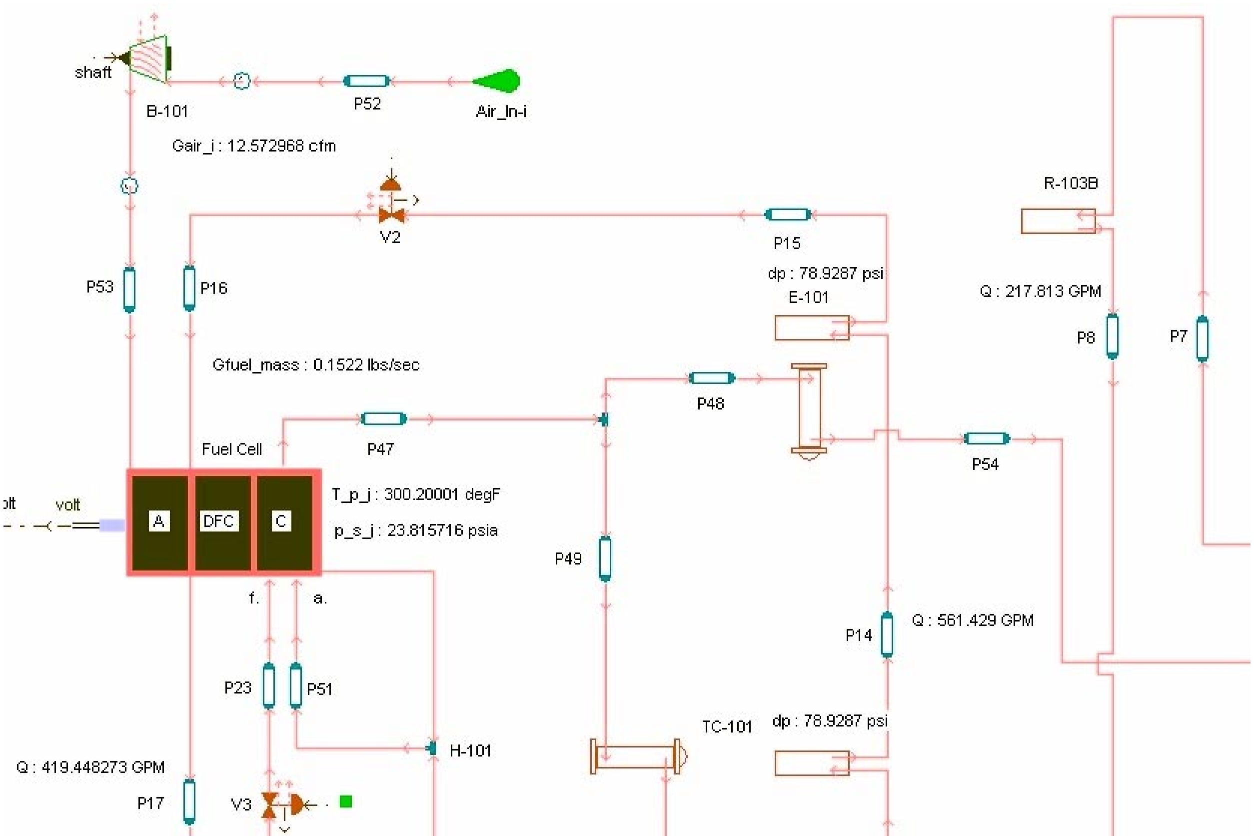


FIGURE 18. SIMSMART SCREEN – CLOSE-UP ABOUT FUEL CELL

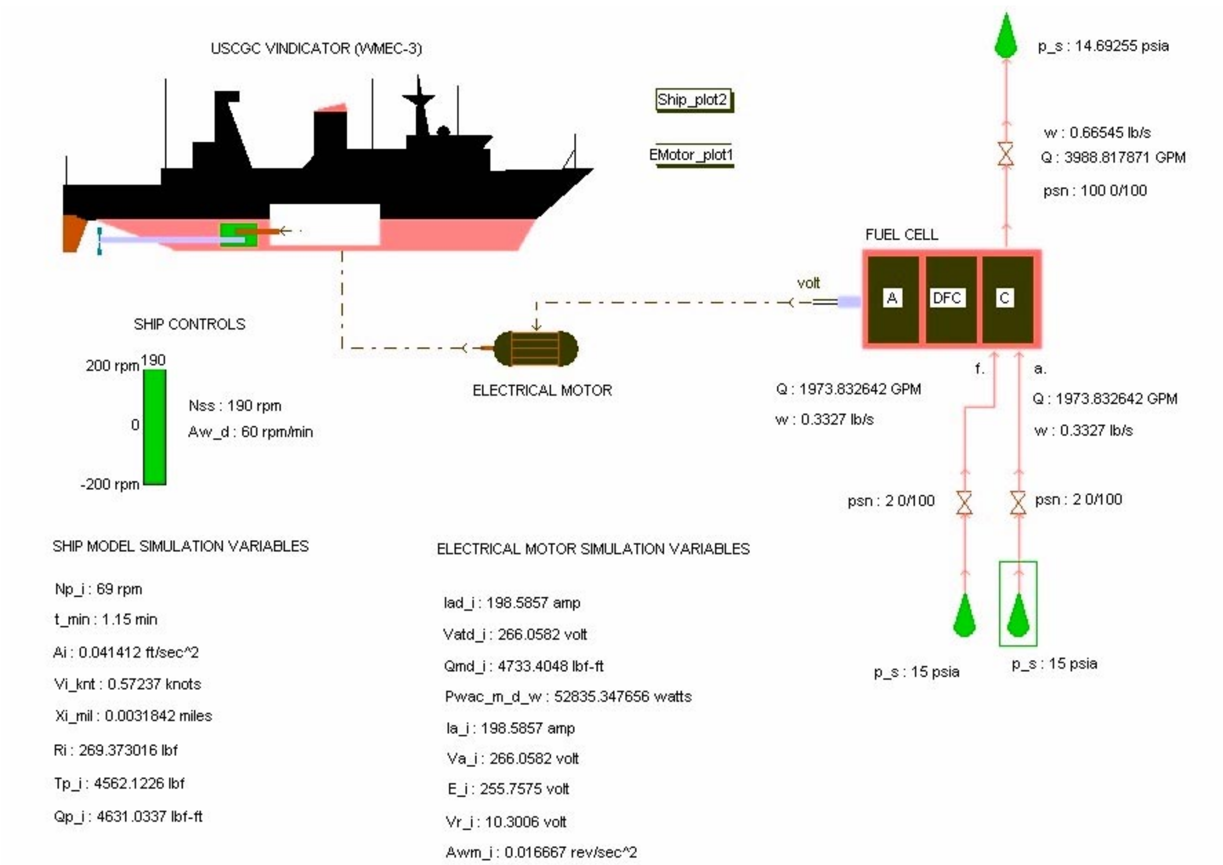


FIGURE 19. SIMSMART SCREEN – SIMPLIFIED WITH SIMULATION VARIABLES

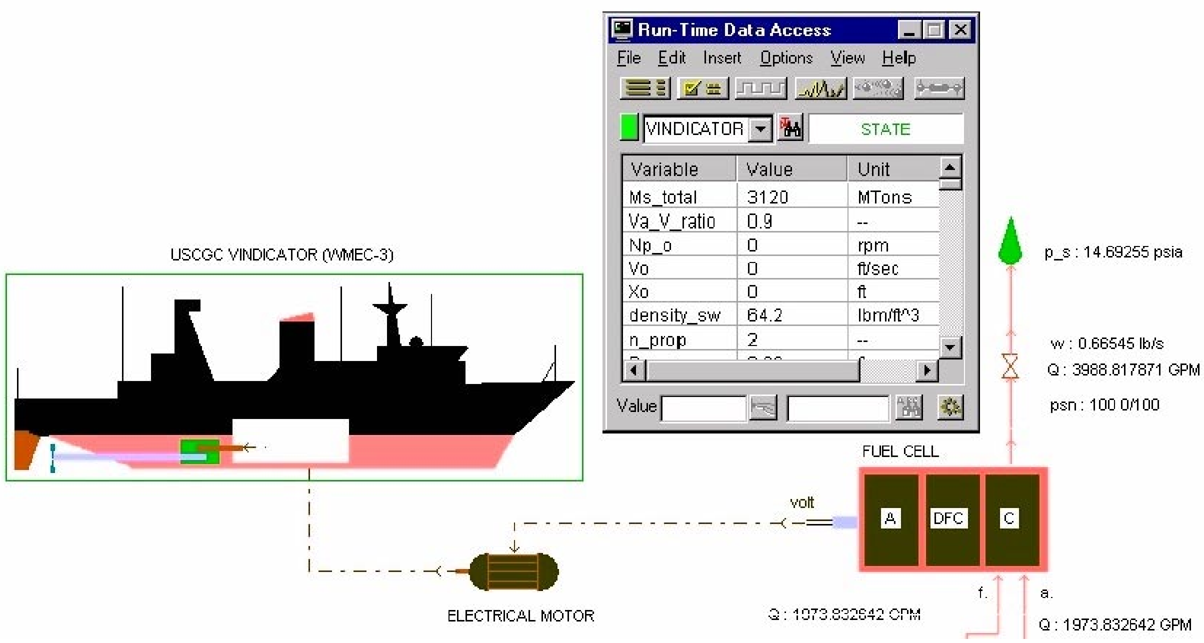


FIGURE 20. SIMSMART SCREEN – SIMPLIED SYSTEM WITH RUN-TIME DATA

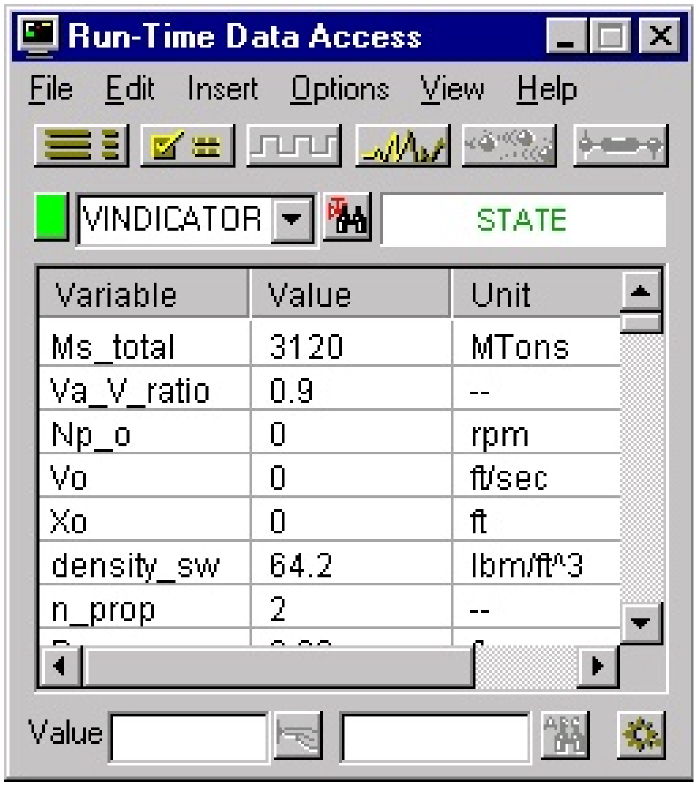


FIGURE 21. SIMSMART SCREEN – RUN-TIME DATA ACCESS PULL DOWN MENU

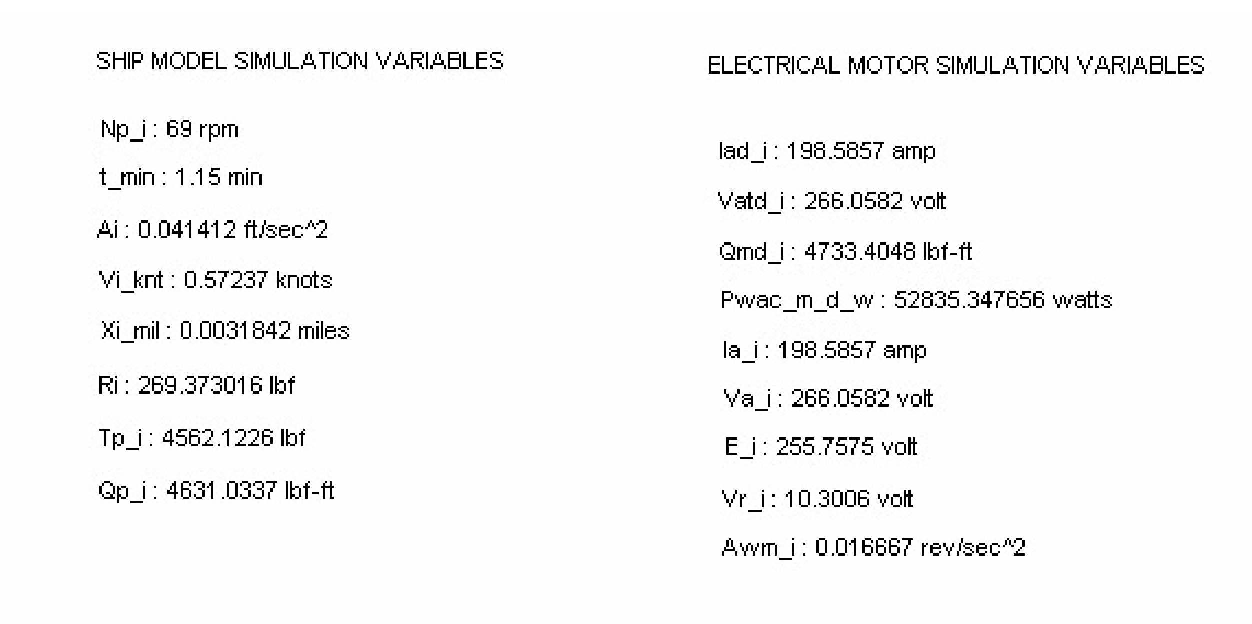


FIGURE 22. SIMSMART SCREEN – SIMULATION VARIABLES

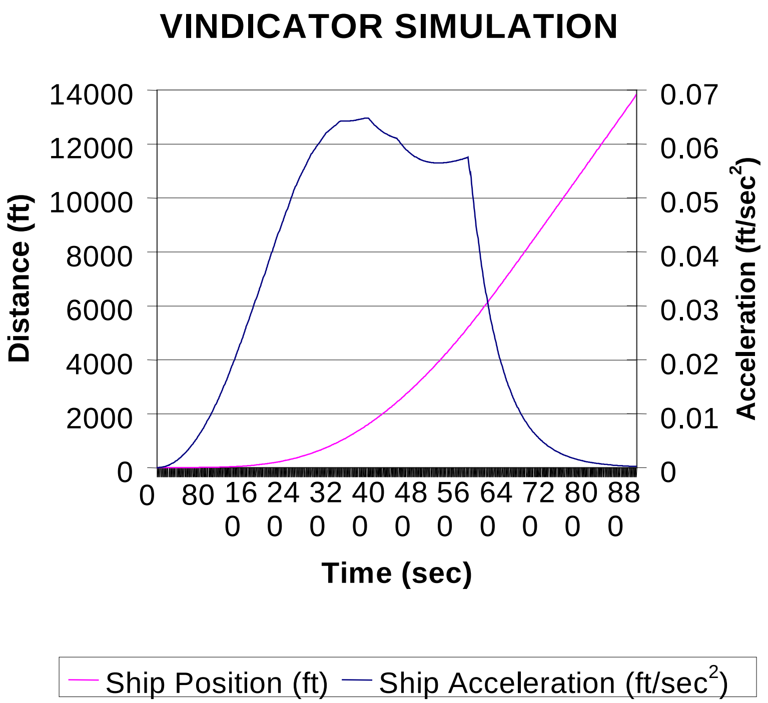


FIGURE 23. SIMSMART OUTPUT SHOWING DISTANCE/ ACCELERATION VS TIME

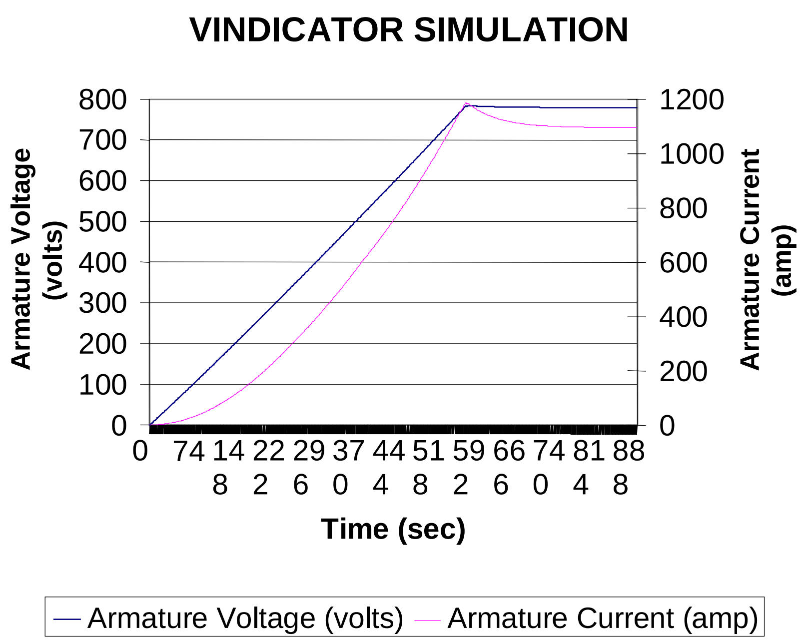
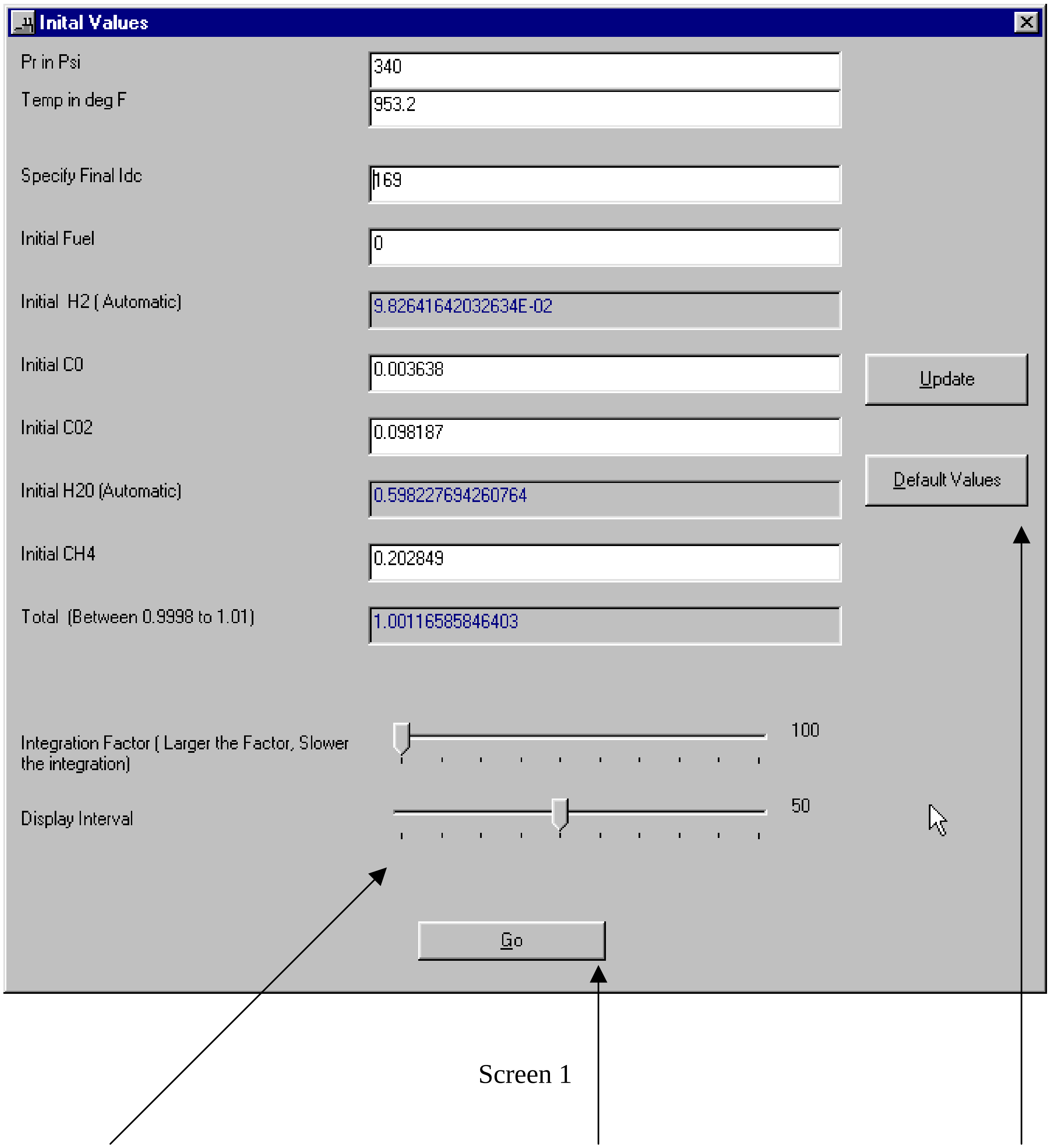


FIGURE 24. SIMSMART OUTPUT SHOWING VOLTS/ AMPERES VERSUS TIME

10.9 Stand-Alone Fuel Cell Simulation Program

A stand-alone fuel cell simulation program of the MCFC primarily depicts the operation characteristics of the pre-reformer. The fuel cell stack is represented by chemical equations representing the conversion of the components of the gases out-flowing from the pre-converter towards the fuel cell stack. The stand-alone fuel cell program is one of the major subroutines in the system's simulation program. The load, VINDICATOR's propulsion motors, send a demand signal requesting the fuel cell to provide the power required to achieve a maneuver. The power requirement is translated by the fuel cell subroutine to the fuel demand, Gfuel, that is delivered instantaneously by the fuel pump to the pre-reformer. The liquid fuel is broken into gas components which in turn generate the required power.

The stand-alone program was modified based on updated sets of equations, as that better represent the proper disturbed initial conditions. Initially the equations undergo spatial integration (with respect to length) in order to establish initial and final gas conditions at sections along the preconverter. A time dependent integration is then performed to simulate the dynamic transients of the gas flowing to the fuel stack. When converted into a SIMSMART subroutine, the extended computational requirement are met by interpolation between pre-calculated sets of results. Typical screens are provided in Figures 25 and 26.

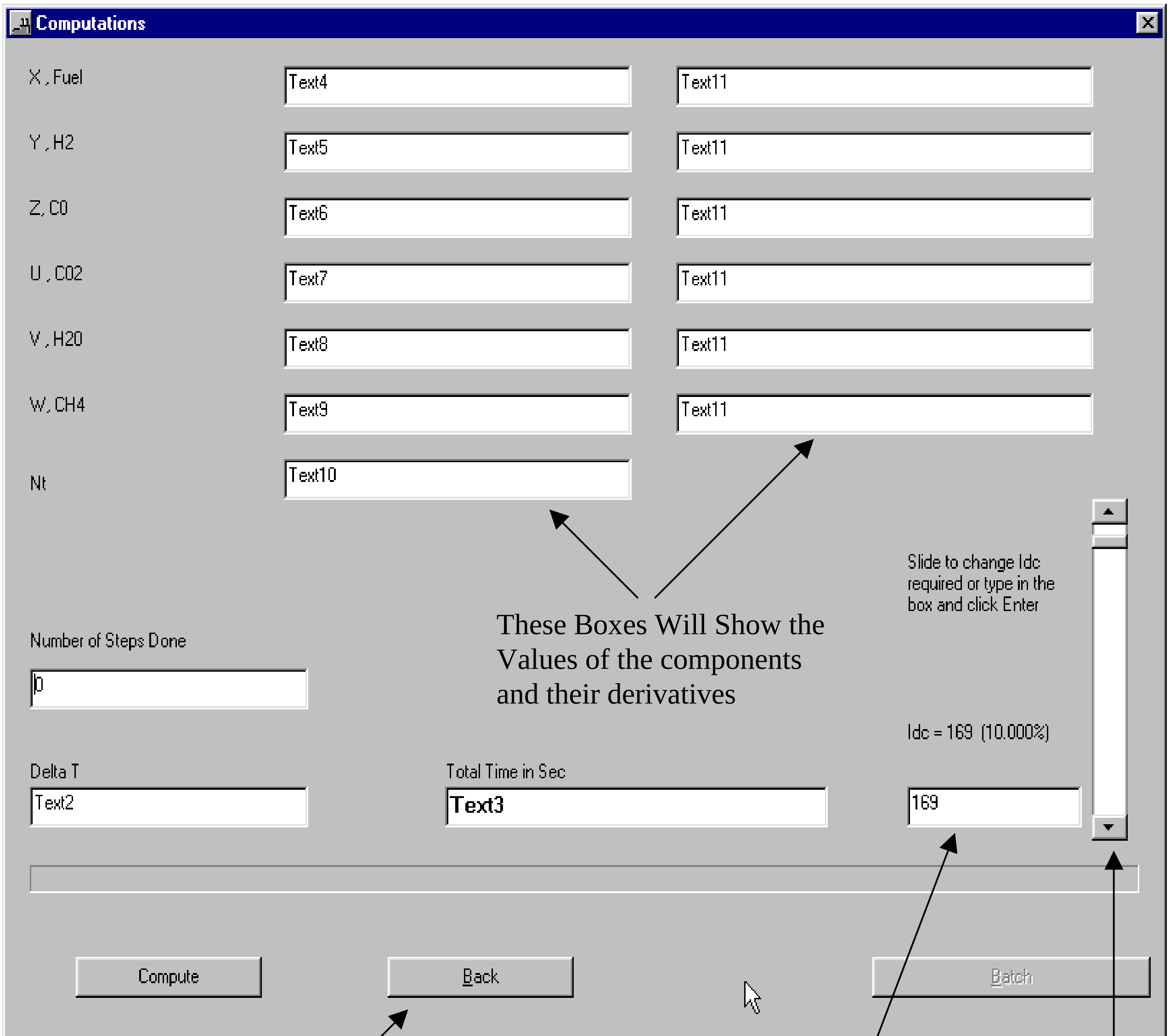


Use the slider to control to change Values.

Click Go to bring display screen 2 and hide this screen.

Click Here to restore Default Values

FIGURE 25. TYPICAL INPUT SIMSMART SCREEN



Screen 2

Click Here to Bring Screen1.
You can change the Integration factor or Display Interval while the program is computing.
To change Initial Conditions Press Stop and then click Back.

Type required Idc Here or slide the Bar.
The Value can be changed during the computations.
Use the Slider as a Fuel Cell power control

FIGURE 26. TYPICAL OUTPUT SIMSMART SCREEN

11.0 SUMMARY

A clear trend towards the design and installation of integrated electric propulsion systems in ships has emerged in the last few years. Most of the new cruise ships employ diesel generators to produce propulsion and hotel power for the ships. The US Navy, as well as many other foreign navies, is considering the use of integrated electric plants in future naval ships. The implementation drivers are primarily lower life cycle cost, and low vibrations and noise levels.

The fuel cell offers several advantages over diesels. These include higher thermal efficiency (51 vs 35%), a flat efficiency curve, and lower emissions, vibrations, noise, and heat signature. Presently, however, fuel cell initial costs are significantly higher than for diesels, and some additional work is needed on desulfurization and diesel fuel reforming technologies. With further development and cost advantages from mass production, MCFCs may become competitive with, and even ultimately replace marine diesels.

The US Navy is sponsoring the development of two types of marine fuel cell power modules for the marine industry: a Molten Carbonate (MC) and a Proton Exchange Membrane (PEM) fuel cell. In conjunction with the Navy, the USCG tasked JJMA to develop the ship interfaces required for a MC fuel cell installation and to develop a dynamic simulation incorporating the MC fuel cell as the primary power provider. The USCGC VINDICATOR, a TAGOS 1 Class vessel, was selected as the test bed for this installation study. The ship has an electric integrated propulsion power system powered by four, 600 kW, caterpillar diesel generators and two fixed propeller shafts each powered by 800 hp Direct Current (DC) motor.

This final technical report summarizes several studies which investigated the impact upon the USCGC VINDICATOR ship systems resulting from the replacement of the existing four Caterpillar diesel generators with Molten Carbonate Fuel Cells. It must be noted that during the study of the impact of installing MC fuel cells, the USCG placed the USCGC VINDICATOR in active service making it at least temporarily unavailable as the installation test vessel. However, the space and weight limitations and marine operational requirements uncovered during the several studies are believed to be applicable to similar marine installation applications in the future.

A conceptual arrangement of the machinery space and interfaces with auxiliary systems was developed. The larger dimensions, length, height and width of MC fuel cells compared to diesel generators, require modifications in the machinery room. In particular, removal of the void bulkheads on both sides of the machinery room is required in order to provide access to the four fuel cell modules. The machinery service systems, seawater, lubrication oils, fresh water, fuel and compressed air are all affected, although to a relatively minor degree.

The ship’s performance in terms of stability and sea keeping were evaluated and are expected to remain unchanged. Limited maneuvering simulations, ship forward acceleration and reversing, were performed. These simulations showed that the application of power produced by fuel cells is expected to cause insignificant changes in the maneuvering performance of the ship.

The power generation and distribution systems for the ship were originally designed to comply with the Type 1 power requirements of DOD-STD-1399, Section 300. These criteria necessitate the application of diesel generator sets that are in compliance with the transient load requirements of MIL-G-21296 and MIL-G-21410 to ensure that the system power quality is maintained during the large load transients. This final report also provides the technical summary of the Dynamic Simulation Model (DSM) development for the Molten Carbonate, Coast Guard Fuel Cell (MCFC) power plant. It lays the foundation for computer programs and software coding of the DSM and incorporates the vessel's electric propulsion system as a controlled large load typical to ships with an integrated electric propulsion system. A narrative description of the MCFC power plant operation and control strategy is also provided. The governing transient equations related to the fuel cell and the fuel processing are described in detail in the Dynamic Simulation Model (DSM). This model suggests that the Molten Carbonate Fuel Cells do not fully comply with these criteria.

With the current load limiting features inherent in the propulsion system drive controls, the transient response from the currently designed fuel cells is expected to perform well for ship maneuvering power requirement. However, similar to most advanced highly turbocharged diesel generators, the short term transient response does not fully support the requirements of DOD-STD-1399 or the IEEE-STD-45 equivalent. Steps to enhance instantaneous transient response can be incorporated into either the consumer side, or the fuel cell system itself. These can include incorporation of energy accumulators or capacitors in the system. A similar problem occurs with automobiles where improved acceleration is achieved today by adding turbochargers to small, in terms of cylinders and cylinder size, engines or by using multiple power sources such as adding electric battery driven motors to the power system.

Higher thermal efficiency, significantly better part load performance, increasing endurance (range), and reduced vibrations, noise and emissions outweigh the non-compliance with short-term transient requirements. This is especially true in light of the trend to diesel generator (DG) or turbo-generator (TG) powered ships.

The conversion of the power generation system of the USCGC VINDICATOR appears technically and physically feasible. There is sufficient volume and surface area to accommodate equal power Molten Carbonate fuel cells. The interface to the ship's systems is manageable.